

CABLE LINKS AND L-SPACE SURGERIES

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ABSTRACT. An L-space link is a link in S^3 on which all sufficiently large integral surgeries are L-spaces. We prove that for m, n relatively prime, the r -component cable link $K_{rm, rn}$ is an L-space link if and only if K is an L-space knot and $n/m \geq 2g(K) - 1$. We also compute $\widehat{\text{HFL}}^-$ and $\widehat{\text{HFL}}$ of an L-space cable link in terms of its Alexander polynomial. As an application, we confirm a conjecture of Licata [Lic12] regarding the structure of $\widehat{\text{HFL}}$ for (n, n) torus links.

1. INTRODUCTION

Heegaard Floer homology is a package of 3-manifold invariants defined by Ozsváth and Szabó [OS04a, OS04b]. In its simplest form, it associates to a closed 3-manifold Y a graded vector space $\widehat{\text{HF}}(Y)$. For a rational homology sphere Y , they show that

$$\dim \widehat{\text{HF}}(Y) \geq |H_1(Y; \mathbb{Z})|.$$

If equality is achieved, then Y is called an *L-space*.

A knot $K \subset S^3$ is an *L-space knot* if K admits a positive L-space surgery. Let $S_{p/q}^3(K)$ denote p/q Dehn surgery along K . If K is an L-space knot, then $S_{p/q}^3(K)$ is an L-space for all $p/q \geq 2g(K) - 1$, where $g(K)$ denotes the Seifert genus of K [OS11, Corollary 1.4]. A link $L \subset S^3$ is an *L-space link* if all sufficiently large integral surgeries on L are L-spaces. In contrast to the knot case, if L admits a positive L-space surgery, it does not necessarily follow that all sufficiently large surgeries are also L-spaces; see [Liu14, Example 2.3].

For relatively prime integers m and n , let $K_{m,n}$ denote the (m, n) cable of K , where m denotes the longitudinal winding. Without loss of generality, we will assume that $m > 0$. Work of Hedden [Hed09] (“if” direction) and the second author [Hom11] (“only if” direction) completely classifies L-space cable knots.

Theorem 1 ([Hed09, Hom11]). *Let K be a knot in S^3 , $m > 1$ and $\gcd(m, n) = 1$. The cable knot $K_{m,n}$ is an L-space knot if and only if K is an L-space knot and $n/m > 2g(K) - 1$.*

Remark 1.1. Note that when $m = 1$, we have that $K_{1,n} = K$ for all n .

We generalize this theorem to cable links with many components. Throughout the paper, we assume that each component of a cable link is oriented in the same direction.

Theorem 2. *Let K be a knot in S^3 and $\gcd(m, n) = 1$. The r -component cable link $K_{rm, rn}$ is an L-space link if and only if K is an L-space knot and $n/m \geq 2g(K) - 1$.*

In [OS05], Ozsváth and Szabó show that if K is an L-space knot, then $\widehat{\text{HFK}}(K)$ is completely determined by $\Delta_K(t)$, the Alexander polynomial of K . Consequently, the Alexander polynomials of L-space knots are quite constrained (the non-zero coefficients are all ± 1 and alternate in sign)

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and the rank of $\widehat{\text{HFK}}(K)$ is at most one in each Alexander grading. In [Liu14, Theorem 1.15], Liu generalizes this result to give bounds on the rank of $\text{HFL}^-(L)$ in each Alexander multi-grading and on the coefficients of the multi-variable Alexander polynomial of an L-space link L in terms of the number of components of L . For L-space cable links, we have the following stronger result.

Definition 1.2. Define the \mathbb{Z} -valued functions $\mathbf{h}(k)$ and $\beta(k)$ by the equations:

$$(1.1) \quad \sum_k \mathbf{h}(k)t^k = \frac{t^{-1}\Delta_{m,n}(t)(t^{mn/2} - t^{-mn/2})}{(1-t^{-1})^2(t^{mn/2} - t^{-mn/2})}, \quad \beta(k) = \mathbf{h}(k-1) - \mathbf{h}(k) - 1,$$

where $\Delta_{m,n}(t)$ is the Alexander polynomial of the cable knot $K_{m,n}$.

Throughout, we work with $\mathbb{F} = \mathbb{Z}/2\mathbb{Z}$ coefficients. The following theorem gives a complete description of the homology groups $\widehat{\text{HFL}}$ for cable links with $n/m > 2g(K) - 1$.

Theorem 3. *Let $K_{rm, rn}$ be a cable link with $n/m > 2g(K) - 1$.*

(a) *If $\beta(k) + \beta(k+1) \leq r - 2$ then:*

$$\widehat{\text{HFL}}(K_{rm, rn}, k, \dots, k) \simeq \bigoplus_{i=0}^{\beta(k)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)-i} \oplus \bigoplus_{i=0}^{\beta(k+1)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)+2-r+i}$$

(b) *If $\beta(k) + \beta(k+1) \geq r - 2$ then:*

$$\widehat{\text{HFL}}(K_{rm, rn}, k, \dots, k) \simeq \bigoplus_{i=0}^{r-2-\beta(k+1)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)-i} \oplus \bigoplus_{i=0}^{r-2-\beta(k)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)+2-r+i}$$

(c) *If v has j coordinates equal to $k - 1$ and $r - j$ coordinates equal to k for some k and $1 \leq j \leq r - 1$, then:*

$$\widehat{\text{HFL}}(K_{rm, rn}, (k-1)^j, k^{r-j}) \simeq \binom{r-2}{\beta(k)} \mathbb{F}_{-2\mathbf{h}(k)-\beta(k)-j}.$$

(d) *For all other Alexander gradings the groups $\widehat{\text{HFL}}$ vanish.*

We prove the parts of this theorem as separate Theorems 4.22, 4.24 and 4.25. We compute $\widehat{\text{HFL}}$ explicitly for several examples in Section 5. In particular, we use Theorem 3 to confirm a conjecture of Joan Licata [Lic12, Conjecture 1] concerning $\widehat{\text{HFL}}$ for (n, n) torus links.

Theorem 4. *Suppose that $0 \leq s \leq \frac{n-1}{2}$. Then*

$$\widehat{\text{HFL}}\left(T(n, n), \frac{n-1}{2} - s, \dots, \frac{n-1}{2} - s\right) = \bigoplus_{i=0}^s \binom{n-1}{i} \mathbb{F}_{(-s^2-s-i)} \oplus \bigoplus_{i=0}^{s-1} \binom{n-1}{i} \mathbb{F}_{(-s^2-s-n+2+i)}.$$

Combined with [Lic12, Theorem 2], this completes the description of $\widehat{\text{HFL}}(T(n, n))$.

The following theorem describes the homology groups HFL^- for cable links with $n/m > 2g(K) - 1$.

Theorem 5. *Let K be an L-space knot and $n/m > 2g(K) - 1$. Consider an Alexander grading $v = (v_1, \dots, v_n)$. Suppose that among the coordinates v_i exactly λ are equal to k and all other coordinates are less than k . Let $|v| = v_1 + \dots + v_n$. Then the Heegaard-Floer homology group $\text{HFL}^-(K_{rm, rn}, v)$ can be described as follows:*

(a) *If $\beta(k) < r - \lambda$ then $\text{HFL}^-(K_{rm, rn}, v) = 0$.*

(b) If $\beta(k) \geq r - \lambda$ then

$$\mathrm{HFL}^-(K_{rm, rn}, v) \simeq (\mathbb{F}_{(0)} \oplus \mathbb{F}_{(-1)})^{r-\lambda} \otimes \bigoplus_{i=0}^{\beta(k)-r+\lambda} \binom{\lambda-1}{i} \mathbb{F}_{(-2h(v)-i)},$$

where $h(v) = \mathbf{h}(k) + kr - |v|$.

We prove this theorem in Section 4.2. The structure of the homology for $n/m = 2g(K) - 1$ (which is possible only if $m = 1$) is more subtle and is described in Theorem 4.26.

Finally, we describe HFL^- as an $\mathbb{F}[U_1, \dots, U_r]$ -module. We define a collection of $\mathbb{F}[U_1, \dots, U_r]$ -modules M_β for $0 \leq \beta \leq r - 2$, $M_{r-1, k}$ for $k \geq 0$ and $M_{r-1, \infty}$. These modules can be defined combinatorially and do not depend on a link.

Theorem 6. *Let $R = \mathbb{F}[U_1, \dots, U_r]$ and suppose that $n/m > 2g(K) - 1$. There exists a finite collection of diagonal lattice points $\mathbf{a}_i = (a_i, \dots, a_i)$ (determined by m, n and the Alexander polynomial of K) such that HFL^- admits the following direct sum decomposition:*

$$\mathrm{HFL}^-(K_{rm, rn}) = \bigoplus_i R \cdot \mathrm{HFL}^-(K_{rm, rn}, \mathbf{a}_i).$$

Furthermore, for $\beta(a_i) \leq r - 2$ one has $R \cdot \mathrm{HFL}^-(K_{rm, rn}, \mathbf{a}_i) \simeq M_{\beta(a_i)}$, and for $\beta(a_i) = r - 1$ one has either $R \cdot \mathrm{HFL}^-(K_{rm, rn}, \mathbf{a}_i) \simeq M_{r-1, k}$ for some k or $R \cdot \mathrm{HFL}^-(K_{rm, rn}, \mathbf{a}_i) \simeq M_{r-1, \infty}$.

We compute HFL^- explicitly for several examples in Section 5.

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2. DEHN SURGERY AND CABLE LINKS

In this section, we prove Theorem 2. We begin with a result about Dehn surgery on cable links (cf. [Hei74]).

Proposition 2.1. *The manifold obtained by (mn, p_2, \dots, p_r) -surgery on the r -component link $K_{rm, rn}$ is homeomorphic to $S^3_{n/m}(K) \# L(m, n) \# L(p_2 - mn, 1) \# \dots \# L(p_r - mn, 1)$.*

Proof. Recall (see, for example, [Hed09, Section 2.4]) that mn -surgery on $K_{m, n}$ gives the manifold $S^3_{n/m}(K) \# L(m, n)$. Viewing $K_{m, n}$ as the image of $T_{m, n}$ on $\partial N(K)$, we have that the reducing sphere is given by the annulus $\partial N(K) \setminus N(T_{m, n})$ union two parallel copies of the meridional disk of the surgery solid torus; we obtain a sphere since the surgery slope coincides with the surface framing.

The link $K_{rm, rn}$ consists of r parallel copies of $K_{m, n}$ on $\partial N(K)$. Label these r copies $K_{m, n}^1$ through $K_{m, n}^r$. We perform mn -surgery on $K_{m, n}^1$ and consider the image $\tilde{K}_{m, n}^i$ of $K_{m, n}^i$, $2 \leq i \leq r$, in $S^3_{n/m}(K) \# L(m, n)$. Each $\tilde{K}_{m, n}^i$ lies on $\partial N(K) \setminus N(T_{m, n})$ and thus on the reducing sphere. In particular, each $\tilde{K}_{m, n}^i$ bounds a disk D_i^2 in $S^3_{n/m}(K) \# L(m, n)$ such that the collection $\{D_2^2, \dots, D_r^2\}$ is disjoint. It follows that performing surgery on $\bigcup_{i=2}^r \tilde{K}_{m, n}^i$ yields $r - 1$ lens space summands. To see which lens spaces we obtain, note that the mn -framed longitude on $K_{m, n}^i \subset S^3$ coincides with the 0-framed longitude on $\tilde{K}_{m, n}^i \subset S^3_{n/m}(K) \# L(m, n)$. Thus, p_i -surgery on $K_{m, n}^i$ corresponds to $(p_i - mn)$ -surgery on $\tilde{K}_{m, n}^i$, and the result follows. \square

Let us recall that the linking number between each two components of $K_{rm, rn}$ equals $l := mn$. It is well-known that the cardinality of H_1 of the manifold obtained by (p_1, p_2, \dots, p_r) -surgery on $K_{rm, rn}$ equals $|\det \Lambda(p_1, \dots, p_r)|$, where

$$\Lambda_{ij} = \begin{cases} p_i, & \text{if } i = j, \\ l, & \text{if } i \neq j. \end{cases}$$

This cardinality can be computed using the following result.

Proposition 2.2. *One has the following identity:*

$$(2.1) \quad \det \Lambda(p_1, \dots, p_r) = (p_1 - l) \cdots (p_r - l) + l \sum_{i=1}^r (p_1 - l) \cdots \widehat{(p_i - l)} \cdots (p_r - l).$$

Proof. One can easily check that $\det \Lambda(l, p_2, \dots, p_r) = l(p_2 - l) \cdots (p_r - l)$. The expansion of the determinant in the first row yields a recursion relation

$$\begin{aligned} \det \Lambda(p_1, \dots, p_r) &= \det \Lambda(l, p_2, \dots, p_r) + (p_1 - l) \det \Lambda(p_2, \dots, p_r) \\ &= l(p_2 - l) \cdots (p_r - l) + (p_1 - l) \det \Lambda(p_2, \dots, p_r). \end{aligned}$$

Now (2.1) follows by induction in r . □

Corollary 2.3. *If $p_i \geq l$ for all i then $\det \Lambda(p_1, \dots, p_r) \geq 0$.*

In order to prove Theorem 2, we will need the following:

Theorem 2.4 ([Liu14, Proposition 1.11]). *A link L is an L -space link if and only if there exists a surgery framing $\Lambda(p_1, \dots, p_r)$, such that for all sublinks $L' \subseteq L$, $\det(\Lambda(p_1, \dots, p_r)|_{L'}) > 0$ and $S^3_{\Lambda|_{L'}}(L')$ is an L -space.*

We will also need the following proposition, which we prove in Subsection 2.1 below.

Proposition 2.5. *Let K be an L -space knot and $p_i > 0$, $i = 1, \dots, r$. If $n < 2g(K) - 1$, then the manifold obtained by (p_1, \dots, p_r) -surgery on the r -component link $K_{r, rn}$ is not an L -space.*

Proof of Theorem 2. If $K_{rm, rn}$ is an L -space link, then by [Liu14, Lemma 1.10] all its components are L -space knots. On the other hand, its components are isotopic to $K_{m, n}$. Thus, if $m > 1$, then by Theorem 1, K is an L -space knot and $n/m > 2g(K) - 1$. If $m = 1$, then K must be an L -space knot and by Proposition 2.5, $n \geq 2g(K) - 1$.

Conversely, suppose that K is an L -space knot and $n/m \geq 2g(K) - 1$, i.e., $K_{m, n}$ is an L -space knot. Let us prove by induction on r that (p_1, \dots, p_r) -surgery on $K_{rm, rn}$ is an L -space if $p_i > l$ for all i . For $r = 1$ it is clear. By Proposition 2.1, the link $K_{rm, rn}$ admits an L -space surgery with parameters l, p_2, \dots, p_r . Let us apply Theorem 2.4. Indeed, by Corollary 2.3, one has $\det(\Lambda(l, p_2, \dots, p_r)|_{L'}) > 0$ and by the induction assumption $S^3_{\Lambda(l, p_2, \dots, p_r)|_{L'}}(L')$ is an L -space for all sublinks L' . By [Liu14, Lemma 2.5], (p_1, \dots, p_r) -surgery on $K_{rm, rn}$ is also an L -space for all $p_1 > l$. Therefore $K_{rm, rn}$ is an L -space link. □

2.1. Proof of Proposition 2.5. We will prove Proposition 2.5 using Lipshitz-Ozsváth-Thurston's bordered Floer homology [LOT08], specifically Hanselman-Watson's [HW15] loop calculus. That is, we will decompose the result of surgery on $K_{r, rn}$ into two pieces, one that is surgery on a torus link in the solid torus and the other the knot complement, and then apply a gluing result of Hanselman-Watson to conclude that the result of this surgery along $K_{r, rn}$ is not an L -space. The following was described to us by Jonathan Hanselman.

Let Y_1 denote the Seifert fibered space obtained by performing (p_1, \dots, p_r) -surgery on the r -component $(r, 0)$ -torus link in the solid torus. Consider the bordered manifold (Y_1, α_1, β_1) , where α_1 is the fiber slope and β_1 lies in the base orbifold; that is, α_1 is the longitude and β_1 the meridian of the original solid torus. Let (Y_2, α_2, β_2) be the n -framed complement of K ; that is, $Y_2 = S^3 \setminus N(K)$, α_2 is an n -framed longitude, and β_2 is a meridian. Let $(Y_1, \alpha_1, \beta_1) \cup (Y_2, \alpha_2, \beta_2)$ denote the result of gluing Y_1 to Y_2 by identifying α_1 with α_2 and β_1 with β_2 . Note that $(Y_1, \alpha_1, \beta_1) \cup (Y_2, \alpha_2, \beta_2)$ is homeomorphic to (p_1, \dots, p_r) -surgery along $K_{r, rn}$. We identify the slope $p\alpha_i + q\beta_i$ on ∂Y_i with the (extended) rational number $\frac{p}{q} \in \mathbb{Q} \cup \{\frac{1}{0}\}$.

The following lemma gives a description of $\widehat{\text{CFD}}(Y_1, \alpha_1, \beta_1)$ in terms of the standard notation defined in [HW15, Section 3.2].

Lemma 2.6. *The invariant $\widehat{\text{CFD}}(Y_1, \alpha_1, \beta_1)$ can be written in standard notation as a product of d_{k_i} where*

- (1) $k_i \leq 0$ for all i ,
- (2) $k_i = 0$ for at least one i ,
- (3) $k_i = -r$ for exactly one i .

Proof. The computation is similar to the example in [HW15, Section 6.5]. A plumbing tree Γ for Y_1 is given in Figure 1. We first consider the plumbing tree Γ_i in Figure 2(a). We will build Γ by merging the Γ_i , $i = 1, \dots, r$.

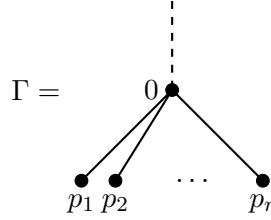
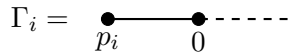


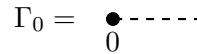
FIGURE 1. The plumbing tree Γ .

We proceed as in [HW15, Section 6.5]. Start with a loop (d_0) representing the tree Γ_0 in Figure 2(b). We have that $\Gamma_i = \mathcal{E}(\mathcal{T}^{p_i}(\Gamma_0))$ so by [HW15, Sections 3.3 and 6.3]:

$$\begin{aligned}
 \widehat{\text{CFD}}(\Gamma_i) &= \text{E}(\mathcal{T}^{p_i}((d_0))) \\
 &= \text{E}((d_{p_i})) \\
 &= (d_{-p_i}^*) \\
 &\sim (d_{-1} \underbrace{d_0 \dots d_0}_{p_i}).
 \end{aligned}$$



(a)



(b)

FIGURE 2. Left, the plumbing tree Γ_i . Right, the plumbing tree Γ_0 .

We then have that $\Gamma = \mathcal{M}(\Gamma_2, \mathcal{M}(\Gamma_2, \dots, \mathcal{M}(\Gamma_{p_{r-1}}, \Gamma_{p_r})))$. By [HW15, Proposition 6.4], we have that $\widehat{\text{CFD}}(\Gamma)$ is represented by a product of d_{k_i} where $k_i \leq 0$ for all i and $k_i = 0$ for at least one i since each $p_i > 0$. Moreover, d_{-r} appears exactly once in the product, since we performed $r - 1$ merges. This completes the proof of the lemma. \square

Lemma 2.7. *The slope 1 is not a strict L-space slope on (Y_1, α_1, β_1) .*

Proof. We will apply a positive Dehn twist to (Y_1, α_1, β_1) to obtain $(Y_1, \alpha_1, \beta_1 + \alpha_1)$. We will show that 0 is not a strict L-space slope on $(Y_1, \alpha_1, \beta_1 + \alpha_1)$, and hence 1 is not a strict L-space slope on (Y_1, α_1, β_1) .

By [HW15, Proposition 6.1], we have that $\widehat{\text{CFD}}(Y_1, \alpha_1, \beta_1 + \alpha_1)$ can be obtained by applying T to a loop representative of $\widehat{\text{CFD}}(Y_1, \alpha_1, \beta_1)$. Since $T(d_k) = d_{k+1}$, it follows from Lemma 2.6 that $\widehat{\text{CFD}}(Y_1, \alpha_1, \beta_1 + \alpha_1)$ can be written in standard notation as a product of d_{k_i} with $k_i \leq 1$ for all i , $k_i = 1$ for at least one i , and $k_i = 1 - r$ for exactly one i .

We claim that if a loop ℓ contains both positive and negative d_k segments (i.e., both $d_i, i > 0$ and $d_j, j < 0$), then in dual notation ℓ contains at least one a_i^* or b_j^* segment. Indeed, suppose by contradiction that ℓ has no a_i^* or b_j^* . Then ℓ consists of only d_i^* segments, $i \in \mathbb{Z}$. It is straightforward to see (for example, by considering the segments as drawn in [HW15, Figure 1]) that one cannot obtain a loop containing both positive and negative d_k segments from d_i^* segments, $i \in \mathbb{Z}$. This completes the proof of the claim.

Furthermore, note that $\widehat{\text{CFD}}(Y_1, \alpha_1, \beta_1 + \alpha_1)$ consists of simple loops (see Definition 4.19 of [HW15]). Then by [HW15, Proposition 4.24], in dual notation ℓ has no a_k^* or b_k^* segments for $k < 0$. It now follows from Proposition 4.18 of [HW15] that 0 is not a strict L-space slope for $\widehat{\text{CFD}}(Y_1, \alpha_1, \beta_1 + \alpha_1)$. Therefore, 1 is not a strict L-space slope on (Y_1, α_1, β_1) , as desired. \square

Remark 2.8. Note that by Proposition 4.18 of [HW15], we have that 0 and ∞ are strict L-space slopes on (Y_1, α_1, β_1) . Since 1 is not a strict L-space slope, it follows from Corollary 4.5 of [HW15] that the interval of L-space slopes of (Y_1, α_1, β_1) contains the interval $[-\infty, 0]$.

Remark 2.9. An alternative proof of Lemma 2.7 follows from [LS07, Theorem 1.1]. Indeed, by setting $r_i = 1/p_i$ and $e_0 = -1$ in Figure 1 of [LS07], we see that $M(-1; 1/p_1, \dots, 1/p_r)$ is not an L-space, hence neither is $M(1; -1/p_1, \dots, -1/p_r)$, which is homeomorphic to filling (Y_1, α_1, β_1) along a curve of slope 1.

Lemma 2.10. *Let K be an L-space knot. If $n < 2g(K) - 1$, then 1 is not a strict L-space slope on the n -framed knot complement (Y_2, α_2, β_2) .*

Proof. Since K is an L-space knot, we have that $S_K^3(p/q)$ is an L-space exactly when $p/q \geq 2g(K) - 1$. Since α_2 is an n -framed longitude, it follows that the interval of strict L-space slopes on (Y_2, α_2, β_2) is $(0, \frac{1}{2g(K)-1-n})$, that is, the reciprocal of the interval $(2g(K) - 1 - n, \infty)$. \square

Proof of Proposition 2.5. The result now follows from [HW15, Theorem 1.3] combined with Lemmas 2.7 and 2.10; the slope 1 is not a strict L-space slope on either (Y_1, α_1, β_1) or (Y_2, α_2, β_2) , and so the resulting manifold $(Y_1, \alpha_1, \beta_1) \cup (Y_2, \alpha_2, \beta_2)$, which is (p_1, \dots, p_r) -surgery on $K_{r, rn}$, is not an L-space. \square

Remark 2.11. One can use similar methods to provide an alternate proof that $K_{r, rn}$ is an L-space link if K is an L-space knot and $n \geq 2g(K) - 1$. Indeed, if K is an L-space knot, then the interval of strict L-space slopes on the n -framed knot complement (Y_2, α_2, β_2) is $(0, \frac{1}{2g(K)-1-n})$ if $n \leq 2g(K) - 1$ and $(0, \infty] \cup [-\infty, \frac{1}{2g(K)-1-n})$ if $n > 2g(K) - 1$. Hence if $n \geq 2g(K) - 1$, then the

interval of strict L-space slopes on (Y_2, α_2, β_2) contains the interval $(0, \infty)$. By Remark 2.8, we have that the interval of strict L-space slopes on (Y_1, α_1, β_1) contains $[-\infty, 0]$. Therefore, by [HW15, Theorem 1.4], if $n \geq 2g(K) = 1$, then the result of positive surgery (i.e., each surgery coefficient is positive) on $K_{r, rn}$ is an L-space.

3. A SPECTRAL SEQUENCE FOR L-SPACE LINKS

In this section we review some material from [GN15]. Given $u, v \in \mathbb{Z}^r$, we write $u \preceq v$ if $u_i \leq v_i$ for all i , and $u \prec v$ if $u \preceq v$ and $u \neq v$. Recall that we work with $\mathbb{F} = \mathbb{Z}/2\mathbb{Z}$ coefficients.

Definition 3.1. Given a r -component oriented link L , we define an affine lattice over \mathbb{Z}^r :

$$\mathbb{H}(L) = \bigoplus_{i=1}^r \mathbb{H}_i(L), \quad \mathbb{H}_i(L) = \mathbb{Z} + \frac{1}{2} \text{lk}(L_i, L - L_i).$$

Let us recall that the Heegaard-Floer complex for a r -component link L is naturally filtered by the subcomplexes $A_L^-(L; v)$ of $\mathbb{F}[U_1, \dots, U_r]$ -modules for $v \in \mathbb{H}(L)$. Such a subcomplex is spanned by the generators in the Heegaard-Floer complex of Alexander filtration less than or equal to v in the natural partial order on $\mathbb{H}(L)$. The group $\text{HFL}^-(L, v)$ can be defined as the homology of the associated graded complex:

$$(3.1) \quad \text{HFL}^-(L, v) = H_* \left(A^-(L; v) / \sum_{u \prec v} A^-(L; u) \right).$$

One can forget a component L_r in L and consider the $(r-1)$ -component link $L - L_r$. There is a natural forgetful map $\pi_r : \mathbb{H}(L) \rightarrow \mathbb{H}(L - L_r)$ defined by the equation:

$$\pi_r(v_1, \dots, v_r) = (v_1 - \text{lk}(L_1, L_r)/2, \dots, v_{r-1} - \text{lk}(L_{r-1}, L_r)/2).$$

Similarly, one can define a map $\pi_{L'} : \mathbb{H}(L) \rightarrow \mathbb{H}(L')$ for every sublink $L' \subset L$. Furthermore, for large $v_r \gg 0$ the subcomplexes $A^-(L; v)$ stabilize, and by [OS08, Proposition 7.1] one has a natural homotopy equivalence $A^-(L; v) \sim A^-(L - L_r; \pi_r(v))$. More generally, for a sublink $L' = L_{i_1} \cup \dots \cup L_{i_{r'}}$ one gets

$$(3.2) \quad A^-(L'; \pi_{L'}(v)) \sim A^-(L; v), \text{ if } v_i \gg 0 \text{ for } i \notin \{i_1, \dots, i_{r'}\}.$$

We will use the “inversion theorem” of [GN15], expressing the h -function of a link in terms of the Alexander polynomials of its sublinks, or, equivalently, the Euler characteristics of their Heegaard-Floer homology. Define $\chi_{L,v} := \chi(\text{HFL}^-(L, v))$. Then by [OS08]

$$\chi_L(t_1, \dots, t_r) := \sum_{v \in \mathbb{H}(L)} \chi_{L,v} t_1^{v_1} \dots t_r^{v_r} = \begin{cases} (t_1 \dots t_r)^{1/2} \Delta(t_1, \dots, t_r), & \text{if } r > 1 \\ \Delta(t)/(1 - t^{-1}), & \text{if } r = 1, \end{cases}$$

where $\Delta(t_1, \dots, t_r)$ denotes the *symmetrized* Alexander polynomial.

Remark 3.2. We choose the factor $(t_1 \dots t_r)^{1/2}$ to match more established conventions on the gradings for the hat-version of link Floer homology. For example, the Alexander polynomial of the Hopf link equals 1, and one can check [OS08] that $\widehat{\text{HFL}}$ is supported in Alexander degrees $(\pm \frac{1}{2}, \pm \frac{1}{2})$. Since the maximal Alexander degrees in $\widehat{\text{HFL}}$ and HFL^- coincide, one gets $\chi_{T(2,2)}(t_1, t_2) = t_1^{1/2} t_2^{1/2}$.

The following “large surgery theorem” underlines the importance of $A^-(L; v)$.

Theorem 3.3 ([MO10]). *The homology of $A^-(L; v)$ is isomorphic to the Heegaard-Floer homology of a large surgery on L with spin_c -structure specified by v . In particular, if L is an L-space link, then $H_*(A^-(L, v)) \simeq \mathbb{F}[U]$ for all v and all U_i are homotopic to each other on the subcomplex $A^-(L; v)$.*

One can show that for L-space links the inclusion $h_v : A^-(L, v) \hookrightarrow A^-(S^3)$ is injective on homology, so it is multiplication by $U^{h_L(v)}$. Therefore the generator of $H_*(A^-(L, v)) \simeq \mathbb{F}[U]$ has homological degree $-2h_L(v)$. The function $h_L(v)$ will be called the h -function for an L-space link L . In [GN15] it was called an ‘‘HFL-weight function’’.

Furthermore, if L is an L-space link, then for large $N \in \mathbb{H}(L)$ one has

$$\chi(A^-(L; N)/A^-(L, v)) = h_L(v).$$

Hence, by (3.1) and the inclusion-exclusion formula one can write:

$$(3.3) \quad \chi_{L,v} = \sum_{B \subset \{1, \dots, r\}} (-1)^{|B|-1} h_L(v - e_B),$$

where e_B denotes the characteristic vector of the subset $B \subset \{1, \dots, r\}$. Furthermore, by (3.2) for a sublink $L' = L_{i_1} \cup \dots \cup L_{i_{r'}}$ one gets

$$(3.4) \quad h_{L'}(\pi_{L'}(v)) = h_L(v), \text{ if } v_i \gg 0 \text{ for } i \notin \{i_1, \dots, i_{r'}\}.$$

For $r = 1$ equation (3.3) has the form $\chi_{L,v} = h(v - 1) - h(v)$, so $h(v)$ can be easily reconstructed from the Alexander polynomial: $h_L(v) = \sum_{u \geq v+1} \chi_{L,v}$. For $r > 1$, one can also show that equation (3.3) (together with the boundary conditions (3.4)) has a unique solution, which is given by the following theorem:

Theorem 3.4 ([GN15]). *The h -function of an L-space link is determined by the Alexander polynomials of its sublinks as following:*

$$(3.5) \quad h_L(v_1, \dots, v_r) = \sum_{L' \subseteq L} (-1)^{r'-1} \sum_{u \succeq \pi_{L'}(v+1)} \chi_{L',u},$$

where the sublink L' has r' components and $\mathbf{1} = (1, \dots, 1)$.

Given an L-space link, we construct a spectral sequence whose E_2 page can be computed from the multi-variable Alexander polynomial by an explicit combinatorial procedure, and whose E_∞ page coincides with the group HFL^- . The complex (3.1) is quasi-isomorphic to the iterated cone:

$$\mathcal{K}(v) = \bigoplus_{B \subset \{1, \dots, r\}} A^-(L, v - e_B),$$

where the differential consists of two parts: the first acts in each summand and the second acts by inclusion maps between summands. There is a spectral sequence naturally associated to this construction. Its E_1 term equals

$$E_1(v) = \bigoplus_{B \subset \{1, \dots, r\}} H_*(A^-(L, v - e_B)) = \bigoplus_{B \subset \{1, \dots, r\}} \mathbb{F}[U] \langle z(v - e_B) \rangle,$$

where $z(u)$ is the generator of $H_*(A^-(L, u))$ of degree $-2h_L(u)$. The next differential ∂_1 is induced by inclusions and reads as:

$$(3.6) \quad \partial_1(z(v - e_B)) = \sum_{i \in B} U^{h(v - e_B) - h(v - e_B - e_i)} z(v - e_B + e_i).$$

We obtain the following result.

Theorem 3.5 ([GN15]). *Let L be an L-space link with r components and let $h_L(v)$ be the corresponding h -function. Then there is a spectral sequence with $E_2(v) = H_*(E_1, \partial_1)$ and $E_\infty \simeq \text{HFL}^-(L, v)$.*

Remark 3.6. Let us write more precisely the bigrading on the E_2 page. The E_1 page is naturally bigraded as follows: a generator $U^m z(v - e_B)$ has *cube degree* $|B|$ and its homological degree in $A^-(L, v - e_B)$ equals $-2m - 2h(v - e_B)$. In short, we will write

$$\text{bideg}(U^m z(v - e_B)) = (|B|, -2m - 2h(v - e_B)).$$

The homological degree of the same generator in $E_1(v)$ equals the sum of these two degrees. The differential ∂_1 has bidegree $(-1, 0)$, and, more generally, the differential ∂_k in the spectral sequence has bidegree $(-k, k - 1)$.

In the next section we will compute the E_2 page for cable L-space links and show that $E_2 = E_\infty$. Let us discuss the action of the operators U_i on the E_2 page. Recall that U_i maps $A^-(L, v)$ to $A^-(L, v - e_i)$, and in homology one has:

$$(3.7) \quad U_i z(v) = U^{1-h(v-e_i)+h(v)} z(v - e_i).$$

Since U_i commutes with the inclusions of various A^- , we get the following result.

Proposition 3.7. *Equation (3.7) defines a chain map from $\mathcal{K}(v)$ to $\mathcal{K}(v - e_i)$ commuting with the differential ∂_1 , so we have a well-defined combinatorial map*

$$U_i : H_*(E_1(v), \partial_1) \rightarrow H_*(E_1(v - e_i), \partial_1).$$

If $E_2 = E_\infty$ then one obtains $U_i : \text{HFL}^-(L, v) \rightarrow \text{HFL}^-(L, v - e_i)$.

Furthermore, by the definition of $\widehat{\text{HFL}}$ [OS08, Section 4] one gets:

$$\widehat{\text{HFL}}(L, v) = H_* \left(A^-(L, v) / \left[\sum_{i=1}^r A^-(v - e_i) \oplus \sum_{i=1}^r U_i A^-(v + e_i) \right] \right).$$

This implies the following result:

Proposition 3.8. *There is a spectral sequence with E_1 page*

$$\widehat{E}_1 = \bigoplus_{B \subset \{1, \dots, r\}} \text{HFL}^-(L, v + e_B)$$

and converging to $\widehat{E}_\infty = \widehat{\text{HFL}}(L, v)$. The differential $\widehat{\partial}_1$ is given by the action of U_i induced by (3.7).

4. HEEGAARD-FLOER HOMOLOGY FOR CABLE LINKS

4.1. The Alexander polynomial and h -function. The Alexander polynomial of cable knots and links is given by the following well-known formula:

$$(4.1) \quad \Delta_{K_{rm, rn}}(t_1, \dots, t_r) = \Delta_K(t_1^m \cdots t_r^m) \cdot \Delta_{T(rm, rn)}(t_1, \dots, t_r),$$

where $T(rm, rn)$ denotes the (rm, rn) torus link. Throughout, let $\mathbf{t} = t_1 \cdots t_r$ and $l = mn$.

Lemma 4.1. *The generating functions for the Euler characteristics of HFL^- for $K_{rm, rn}$ and $K_{m, n}$ are related by the following equation:*

$$(4.2) \quad \chi_{K_{rm, rn}}(t_1, \dots, t_r) = \chi_{K_{m, n}}(\mathbf{t}) \cdot (\mathbf{t}^{l/2} - \mathbf{t}^{-l/2})^{r-1}.$$

Proof. The statement follows from the identity (4.1) and the expression for the Alexander polynomials of torus links:

$$\chi_{T(rm, rn)}(t_1, \dots, t_r) = \frac{(\mathbf{t}^{mn/2} - \mathbf{t}^{-mn/2})^r}{(\mathbf{t}^{m/2} - \mathbf{t}^{-m/2})(\mathbf{t}^{n/2} - \mathbf{t}^{-n/2})}.$$

□

Remark 4.2. The Alexander polynomial is determined up to a sign. By (4.2), the multivariable Alexander polynomial of a cable link is supported on the diagonal, so one can fix the sign by requiring its top coefficient to be positive.

From now on we will assume that K is an L-space knot and $n/m \geq 2g(K) - 1$, so $K_{rm, rn}$ is an L-space link for all r . To simplify notation, we define $h_{rm, rn}(v) = h_{K_{rm, rn}}(v)$ and $\chi_{rm, rn}(v) = \chi_{K_{rm, rn}, v}$. Let $c = l(r - 1)/2$.

Theorem 4.3. *Suppose that $v_1 \leq v_2 \leq \dots \leq v_r$. Then the following equation holds:*

$$(4.3) \quad h_{rm, rn}(v_1, \dots, v_r) = h_{m, n}(v_1 - c) + h_{m, n}(v_2 - c + l) + \dots + h_{m, n}(v_r - c + (r - 1)l).$$

Proof. We will use Theorem 3.4 to compute $h(v)$. Let L' be a sublink of $K_{rm, rn}$ with r' components, i.e., $L' = K_{r'm, r'n}$. By (4.2), one has

$$\chi_{K_{r'm, r'n}}(t_1, \dots, t_{r'}) = \chi_{K_{m, n}}(\mathbf{t}) \cdot \mathbf{t}^{l(r'-1)/2} \sum_{j=0}^{r'-1} (-1)^j \binom{r'-1}{j} \mathbf{t}^{-lj},$$

hence $\chi_{L', u}$ does not vanish only if $u = (s, \dots, s)$, and

$$\chi_{L', s, \dots, s} = \sum_{j=0}^{r'-1} (-1)^j \binom{r'-1}{j} \chi_{m, n}(s - l(r' - 1)/2 + lj).$$

Therefore

$$\begin{aligned} \sum_{u \succeq \pi_{L'}(v+1)} \chi_{L', u} &= \sum_{s > \max(\pi_{L'}(v))} \sum_{j=0}^{r'-1} (-1)^j \binom{r'-1}{j} \chi_{m, n}(s - l(r' - 1)/2 + lj) \\ &= \sum_{j=0}^{r'-1} (-1)^j \binom{r'-1}{j} h_{m, n}(\max(\pi_{L'}(v)) - l(r' - 1)/2 + lj). \end{aligned}$$

Furthermore, if $L' = L_{i_1} \cup \dots \cup L_{i_{r'}}$, then $\pi_{L'}(v) = (v_{i_1} - l(r - r')/2, \dots, v_{i_{r'}} - l(r - r')/2)$, so

$$\max(\pi_{L'}(v)) = \max(v_{i_1}, \dots, v_{i_{r'}}) - l(r - r')/2 = \max(v_{L'}) - l(r - r')/2.$$

This means that (3.5) can be rewritten as follows:

$$\begin{aligned} h_{rm, rn}(v_1, \dots, v_r) &= \sum_{L', j} (-1)^{r'-1+j} \binom{r'-1}{j} h_{m, n}(\max(v_{L'}) - l(r - 1)/2 + lj) \\ &= \sum_{i, j} h_{m, n}(v_i - l(r - 1)/2 + lj) \sum_{L': v_i = \max(v_{L'})} (-1)^{r'-1+j} \binom{r'-1}{j}. \end{aligned}$$

One can check that the inner sum vanishes unless $j = i - 1$ (recall that $v_1 \leq v_2 \leq \dots \leq v_r$), so one gets

$$h_{rm, rn}(v_1, \dots, v_r) = \sum_i h_{m, n}(v_i - l(r - 1)/2 + l(i - 1)).$$

□

Lemma 4.4. *The following identity holds:*

$$h_{rm, rn}(-v_1, \dots, -v_r) = h_{rm, rn}(v_1, \dots, v_r) + (v_1 + \dots + v_r).$$

Proof. Suppose that $v_1 \leq v_2 \leq \dots \leq v_r$. Then $-v_1 \geq -v_2 \geq \dots \geq -v_r$. Therefore

$$\begin{aligned} h_{rm, rn}(-v_1, \dots, -v_r) &= \sum_{i=1}^r h_{m, n}(-v_i - l(r-1)/2 + l(r-i)) \\ &= \sum_{i=1}^r h_{m, n}(-v_i + l(r-1)/2 - l(i-1)). \end{aligned}$$

It is known (e.g., [HLZ13]) that for all x ,

$$h_{m, n}(-x) = h_{m, n}(x) + x,$$

hence

$$h_{m, n}(-v_i + l(r-1)/2 - l(i-1)) = h_{m, n}(v_i - l(r-1)/2 + l(i-1)) + (v_i - l(r-1)/2 + l(i-1)).$$

Finally, $\sum_{i=1}^r (-l(r-1)/2 + l(i-1)) = 0$. □

Lemma 4.5. *One has $h_{rm, rn}(k, k, \dots, k) = \mathbf{h}(k)$, where $\mathbf{h}(k)$ is defined by (1.1).*

Proof. Indeed, by (4.3) we have

$$h_{rm, rn}(k, \dots, k) = h_{m, n}(k - l(r-1)/2) + h_{m, n}(k - l(r-1)/2 + l) + \dots + h_{m, n}(k + l(r-1)/2),$$

so

$$\sum_k h_{rm, rn}(k, \dots, k) t^k = (t^{-l(r-1)/2} + \dots + t^{l(r-1)/2}) \sum_k h_{m, n}(k) t^k = \frac{(t^{lr/2} - t^{-lr/2})}{(t^{l/2} - t^{-l/2})} \cdot \frac{t^{-1} \Delta_{m, n}(t)}{(1 - t^{-1})^2}.$$

□

For the rest of this section we will assume that $n/m > 2g(K) - 1$.

Lemma 4.6. *If $v \leq g(K_{m, n}) - l$, then $\text{HFK}^-(K_{m, n}, v) \simeq \mathbb{F}$.*

Proof. By [Hed09, Theorem 1.10], $K_{m, n}$ is an L-space knot and hence by [OS05]

$$g(K_{m, n}) = \tau(K_{m, n}), \quad g(K) = \tau(K).$$

By [Shi85], we have:

$$g(K_{m, n}) = mg(K) + \frac{(m-1)(n-1)}{2},$$

so for $n/m > 2g(K) - 1$ we have

$$2g(K_{m, n}) = 2mg(K) + mn - m - n + 1 < mn + 1,$$

hence $l = mn \geq 2g(K_{m, n})$. On the other hand, it is well-known that for $v \leq -g(K_{m, n})$ one has $\text{HFK}^-(K_{m, n}, v) \simeq \mathbb{F}$. □

We will use the function β defined by (1.1).

Lemma 4.7. *If $\beta(k) = -1$ then $\text{HFK}^-(K_{m, n}, k - c) = 0$. Otherwise*

$$(4.4) \quad \beta(k) = \max\{j : 0 \leq j \leq r-1, \text{HFK}^-(K_{m, n}, k - c + lj) \simeq \mathbb{F}\}.$$

Proof. By (1.1) and Lemma 4.5 we have

$$\beta(k)+1 = h_{rm, rn}(k-1, \dots, k-1) - h_{rm, rn}(k, \dots, k) = \sum_{j=0}^{r-1} (h_{m, n}(k-1-c+l_j) - h_{m, n}(k-c+l_j)).$$

Note that $h_{m, n}(k-1-c+l_j) - h_{m, n}(k-c+l_j) = \dim \text{HFK}^-(K_{m, n}, k-c+l_j) \in \{0, 1\}$. If $\text{HFK}^-(K_{m, n}, k-c+l_j) \simeq \mathbb{F}$ then $k-c+l_j \leq g(K_{m, n})$, so by Lemma 4.6 $\text{HFK}^-(K_{m, n}, k-c+l_{j'}) \simeq \mathbb{F}$ for all $j' < j$. Therefore, if $\text{HFK}^-(K_{m, n}, k-c) = 0$ then $\beta(k) = -1$, otherwise

$$\text{HFK}^-(K_{m, n}, k-c+l_j) = \begin{cases} \mathbb{F} & \text{if } j \leq \beta(k), \\ 0 & \text{if } j > \beta(k). \end{cases}$$

□

Suppose that $v_1 = \dots = v_{\lambda_1} = u_1, v_{\lambda_1+1} = \dots = v_{\lambda_1+\lambda_2} = u_2, \dots, v_{\lambda_1+\dots+\lambda_{s-1}+1} = \dots = v_r = u_s$ where $u_1 < u_2 < \dots < u_s$ and $\lambda_1 + \dots + \lambda_s = r$. We will abbreviate this as $v = (u_1^{\lambda_1}, \dots, u_s^{\lambda_s})$.

Lemma 4.8. *Suppose that $\beta(u_s) < r - \lambda_s$. Then for any subset $B \subset \{1, \dots, r-1\}$ one has $h_{rm, rn}(v - e_B) = h_{rm, rn}(v - e_B - e_r)$.*

Proof. To apply (4.3), one needs to reorder the components of the vectors $v - e_B$ and $v - e_B - e_r$. Note that in both cases the last (largest) λ_s components are equal either to u_s or to $u_s - 1$, and the corresponding contributions to $h_{rm, rn}$ are equal to $h_{m, n}(u_s - c + l(r - \lambda_s) + l_j)$ or to $h_{m, n}(u_s - c + l(r - \lambda_s) + l_j - 1)$, respectively ($j = 0, \dots, \lambda_s - 1$). On the other hand, by (4.4) one has

$$\text{HFK}^-(K_{m, n}, u_s - c + l(r - \lambda_s) + l_j) = 0$$

and so

$$h_{m, n}(u_s - c + l(r - \lambda_s) + l_j - 1) = h_{m, n}(u_s - c + l(r - \lambda_s) + l_j).$$

□

Lemma 4.9. *If $\beta(u_s) \geq r - \lambda_s$ then $h_{rm, rn}(v) = \mathbf{h}(u_s) + ru_s - |v|$.*

Proof. Since $\beta(u_s) \geq r - \lambda_s$, we have $\text{HFK}^-(K_{m, n}, u_s - c + l(r - \lambda_s)) \simeq \mathbb{F}$, so

$$u_s - c + l(r - \lambda_s) \leq g(K_{m, n}).$$

For $i \leq r - \lambda_s$ we get

$$v_i - c + l(i - 1) < u_s - c + l(i - 1) \leq u_s - c + l(r - \lambda_s) - l \leq g(K_{m, n}) - l,$$

so by Lemma 4.6, $\text{HFK}^-(K_{m, n}, w) \simeq \mathbb{F}$ for all $w \in [v_i - c + l(i - 1), u_s - c + l(i - 1)]$, and

$$h_{m, n}(v_i - c + l(i - 1)) = h_{m, n}(u_s - c + l(i - 1)) + (u_s - v_i).$$

Now the statement follows from Lemma 4.3. □

Lemma 4.10. *Suppose that $\beta(u_s) \geq r - \lambda_s$. Then for any subsets $B' \subset \{1, \dots, r - \lambda_s\}$ and $B'' \subset \{r - \lambda_s + 1, \dots, r\}$ one has*

$$h_{rm, rn}(v - e_{B'} - e_{B''}) = h_{rm, rn}(v) + |B'| + \min(|B''|, \beta(u_s) - r + \lambda_s + 1).$$

Proof. Since $\text{HFK}^-(K_{m,n}, u_s - c + l(r - \lambda_s)) \simeq \mathbb{F}$, we have $u_s - c + l(r - \lambda_s) \leq g(K_{m,n})$, so for all $i \leq r - \lambda_s$ one has $v_i - c + l(i - 1) < u_s - c + l(r - \lambda_s) - l \leq g(K_{m,n}) - l$, and by Lemma 4.6 $\text{HFK}^-(K_{m,n}, v_i - c + l(i - 1)) \simeq \mathbb{F}$, and $h_{m,n}(v_i - 1 - c + l(i - 1)) = h_{m,n}(v_i - c + l(i - 1)) + 1$. Therefore $h_{rm, rn}(v - e_{B'} - e_{B''}) = |B'| + h_{rm, rn}(v - e_{B''})$. Finally,

$$\begin{aligned} h_{rm, rn}(v - e_{B''}) - h_{rm, rn}(v) &= \sum_{j=0}^{|B''|} (h_{m,n}(u_s - 1 - c + l(r - \lambda_s) + lj) - h_{m,n}(u_s - c + l(r - \lambda_s) + lj)) \\ &= \min(|B''|, \beta(u_s) - r + \lambda_s + 1). \end{aligned}$$

□

4.2. Spectral sequence for HFL^- .

Definition 4.11. Let \mathcal{E}_r denote the exterior algebra over \mathbb{F} with variables z_1, \dots, z_r . Let us define the *cube differential* on \mathcal{E}_r by the equation

$$\partial(z_{\alpha_1} \wedge \dots \wedge z_{\alpha_k}) = \sum_{j=1}^k z_{\alpha_1} \wedge \dots \wedge \widehat{z_{\alpha_j}} \wedge \dots \wedge z_{\alpha_k},$$

and the *b-truncated differential* on $\mathcal{E}_r[U]$ by the equation

$$\partial^{(b)}(z_{\alpha_1} \wedge \dots \wedge z_{\alpha_k}) = \begin{cases} U\partial(z_{\alpha_1} \wedge \dots \wedge z_{\alpha_k}), & \text{if } k \leq b \\ \partial(z_{\alpha_1} \wedge \dots \wedge z_{\alpha_k}), & \text{if } k > b. \end{cases}$$

More invariantly, one can define the *weight* of a monomial $z_\alpha = z_{\alpha_1} \wedge \dots \wedge z_{\alpha_k}$ as $w(z_\alpha) = \min(|\alpha|, b)$, and the *b-truncated differential* is given by the equation:

$$(4.5) \quad \partial^{(b)}(z_\alpha) = \sum_{i \in \alpha} U^{w(\alpha) - w(\alpha - \alpha_i)} z_{\alpha - \alpha_i}.$$

Indeed, $w(\alpha) - w(\alpha - \alpha_i) = 1$ for $|\alpha| \leq b$ and $w(\alpha) - w(\alpha - \alpha_i) = 0$ for $|\alpha| > b$.

Definition 4.12. Let $\mathcal{E}_r^{\text{red}} \subset \mathcal{E}_r$ be the subalgebra of \mathcal{E}_r generated by the differences $z_i - z_j$ for all $i \neq j$.

Lemma 4.13. *The kernel of the cube differential ∂ on \mathcal{E}_r coincides with $\mathcal{E}_r^{\text{red}}$.*

Proof. It is clear that $\partial(z_i - z_j) = 0$, and Leibniz rule implies vanishing of ∂ on $\mathcal{E}_r^{\text{red}}$. Let us prove that $\text{Ker } \partial \subset \mathcal{E}_r^{\text{red}}$. Since $(\mathcal{E}_r, \partial)$ is acyclic, it is sufficient to prove that the image of every monomial $z_{\alpha_1} \wedge \dots \wedge z_{\alpha_k}$ is contained in \mathcal{E}_r . Indeed, one can check that

$$\partial(z_{\alpha_1} \wedge \dots \wedge z_{\alpha_k}) = (z_{\alpha_2} - z_{\alpha_1}) \wedge \dots \wedge (z_{\alpha_k} - z_{\alpha_{k-1}}).$$

□

Lemma 4.14. *The homology of $\partial^{(b)}$ is given by the following equation:*

$$\dim H_k(\mathcal{E}_r[U], \partial^{(b)}) = \begin{cases} \binom{r-1}{k}, & \text{if } k < b \\ 0, & \text{if } k \geq b. \end{cases}$$

Proof. Since ∂ is acyclic, one immediately gets $H_k(\mathcal{E}_r[U], \partial^{(b)}) = 0$ for $k \geq b$. For $k < b$, the homology is supported at the zeroth power of U and one has $H_k(\mathcal{E}_r[U]) \simeq \text{Ker}(\partial|_{\wedge^k(z_1, \dots, z_r)})$. The dimension of the latter kernel equals

$$\dim \text{Ker}(\partial|_{\wedge^k(z_1, \dots, z_r)}) = \dim \wedge^k(z_1 - z_2, \dots, z_1 - z_r) = \binom{r-1}{k}.$$

□

Proof of Theorem 5. Let us compute $\mathrm{HFL}^-(K_{rm, rn}, v)$ using the spectral sequence constructed in Theorem 3.5. By Lemma 4.8, in case (a) it is easy to see that the complex (E_1, ∂_1) is contractible in the direction of e_r and $E_2 = H_*(E_1, \partial_1) = 0$.

In case (b) by Lemma 4.10 and (4.5) one can write $E_1 = \mathcal{E}_{r-\lambda_s}[U] \otimes_{\mathbb{F}[U]} \mathcal{E}_{\lambda_s}[U]$, a tensor product of chain complexes of $\mathbb{F}[U]$ -modules, and ∂_1 acts as $U\partial$ on the first factor and as $\partial^{(\beta+1)}$ on the second one. This implies

$$(4.6) \quad E_2 = H_*(E_1, \partial_1) \simeq \mathcal{E}_{r-\lambda_s} \otimes_{\mathbb{F}} H_*\left(\mathcal{E}_{\lambda_s}[U], \partial^{(\beta+1)}\right).$$

Indeed, U acts trivially on $H_*(\mathcal{E}_{\lambda_s}[U], \partial^{(\beta+1)})$, so one can take the homology of $\partial^{(\beta+1)}$ first and then observe that $U\partial$ vanishes on

$$\mathcal{E}_{r-\lambda_s}[U] \otimes_{\mathbb{F}[U]} H_*\left(\mathcal{E}_{\lambda_s}[U], \partial^{(\beta+1)}\right) \simeq \mathcal{E}_{r-\lambda_s} \otimes_{\mathbb{F}} H_*\left(\mathcal{E}_{\lambda_s}[U], \partial^{(\beta+1)}\right).$$

By Lemma 4.14, the E_2 page (4.6) agrees with the statement of the theorem, hence we need to prove that the spectral sequence collapses.

Indeed, the E_1 page is bigraded by the homological degree and $|B|$ (see Remark 3.6). By Lemma 4.14 any surviving homology class on the E_2 page of cube degree x has bidegree $(x, -2h_{rm, rn}(v) - 2x)$, so all bidegrees on the E_2 page belong to the same line of slope (-2) . Therefore all higher differentials must vanish.

Finally, a simple formula for $h_{rm, rn}(v)$ in case (b) follows from Lemma 4.9. □

4.3. Action of U_i . One can use Proposition 3.7 to compute the action of U_i on HFL^- for cable links. Recall that $R = \mathbb{F}[U_1, \dots, U_r]$. Throughout this section we assume $n/m > 2g(K) - 1$. We start with a simple algebraic statement.

Proposition 4.15. *Let \mathcal{C} be an \mathbb{F} -algebra. Given a finite collection of elements $c_\alpha \in \mathcal{C}$ and vectors $v^{(\alpha)} \in \mathbb{Z}^r$, consider the ideal $\mathcal{I} \subset \mathcal{C} \otimes_{\mathbb{F}} R$ generated by $c_\alpha \otimes U_1^{v_1^{(\alpha)}} \cdots U_r^{v_r^{(\alpha)}}$. Then the following statements hold:*

- (a) *The quotient $(\mathcal{C} \otimes_{\mathbb{F}} R)/\mathcal{I}$ can be equipped with a \mathbb{Z}^r -grading, with U_i of grading $(-e_i)$ and \mathcal{C} of grading 0.*
- (b) *The subspace of $(\mathcal{C} \otimes_{\mathbb{F}} R)/\mathcal{I}$ with grading v is isomorphic to*

$$[(\mathcal{C} \otimes_{\mathbb{F}} R)/\mathcal{I}](v) \simeq \mathcal{C} / \left(c_\alpha : v^{(\alpha)} \preceq -v \right).$$

Proof. Straightforward. □

Definition 4.16. We define $\mathcal{A}_r = \mathcal{E}_r \otimes_{\mathbb{F}} R$ and $\mathcal{A}_r^{\mathrm{red}} = \mathcal{E}_r^{\mathrm{red}} \otimes_{\mathbb{F}} R$. Let \mathcal{I}'_β denote the ideal in \mathcal{A}_r generated by the monomials $(z_{i_1} \wedge \cdots \wedge z_{i_s}) \otimes U_{i_{s+1}} \cdots U_{i_{\beta+1}}$ for all $s \leq \beta + 1$ and all tuples of pairwise distinct $i_1, \dots, i_{\beta+1}$. Let $\mathcal{I}_\beta := \mathcal{I}'_\beta \cap \mathcal{A}_r^{\mathrm{red}}$ be the corresponding ideal in $\mathcal{A}_r^{\mathrm{red}}$.

The algebras \mathcal{A}_r and $\mathcal{A}_r^{\mathrm{red}}$ are naturally \mathbb{Z}^{r+1} -graded: the generators z_i have Alexander grading 0 and homological grading (-1) , the generators U_i have Alexander grading $(-e_i)$ and homological grading (-2) .

Definition 4.17. We define $\mathcal{H}(k) := \bigoplus_{\max(v) \leq k} \mathrm{HFL}^-(K_{rm, rn}, v)$. Since U_i decreases the Alexander grading, $\mathcal{H}(k)$ is naturally an R -module.

The following theorem clarifies the algebraic structure of Theorem 5.

Theorem 4.18. *The following graded R -modules are isomorphic:*

$$\mathcal{H}(k)/\mathcal{H}(k-1) \simeq \mathcal{A}_r^{\text{red}}/\mathcal{I}_{\beta(k)}[-2\mathbf{h}(k)]\{k, \dots, k\},$$

where $[\cdot]$ and $\{\cdot\}$ denote the shifts of the homological grading and the Alexander grading, respectively.

Proof. By definition, $\mathcal{H}(k)/\mathcal{H}(k-1)$ is supported on the set of Alexander gradings v such that $\max(v) = k$. The monomial $U_1 \cdots U_r$ belongs to the ideal $\mathcal{I}_{\beta(k)}$, so $\mathcal{A}_r^{\text{red}}/\mathcal{I}_{\beta(k)}$ is supported on the set of Alexander gradings u with $\max(u) = 0$.

Suppose that exactly λ components of v are equal to k . Without loss of generality we can assume $v_1, \dots, v_{r-\lambda} < k$ and $v_{r-\lambda+1} = \dots = v_r = k$. It follows from Lemma 4.13 and the proof of Theorem 5 that $\text{HFL}^-(K_{rm, rn}, v)$ is isomorphic to the quotient of $\mathcal{E}_r^{\text{red}}$ by the ideal generated by degree $\beta - r + \lambda + 1$ monomials in $(z_i - z_j)$ for $i, j > r - \lambda$.

Consider the subspace of $\mathcal{A}_r/\mathcal{I}'_\beta$ of Alexander grading $(v_1 - k, \dots, v_r - k)$. By Proposition 4.15 it is isomorphic to a quotient of \mathcal{E}_r modulo the following relations. For each subset $B \subset \{1, \dots, r - \lambda\}$ and each degree $\beta + 1 - |B|$ monomial m' in variables z_i for $i \notin B$ there is a relation $m' \otimes \prod_{b \in B} U_b \in \mathcal{I}'_\beta$. All these relations can be multiplied by an appropriate monomial in R to have Alexander grading $(v_1 - k, \dots, v_r - k)$.

Note that such m' should contain at most $r - \lambda - |B|$ factors with indices in $\{1, \dots, r - \lambda\} \setminus B$, hence it contains at least $\beta - r + \lambda + 1$ factors with indices in $\{r - \lambda + 1, \dots, r\}$. Therefore $[\mathcal{A}_r/\mathcal{I}'_\beta](v_1 - k, \dots, v_r - k)$ is naturally isomorphic to the quotient of \mathcal{E}_r by the ideal generated by degree $\beta - r + \lambda + 1$ monomials in z_i for $i > r - \lambda$.

We conclude that $[\mathcal{A}_r^{\text{red}}/\mathcal{I}_{\beta(k)}](v_1 - k, \dots, v_r - k)$ is isomorphic to $\text{HFL}^-(K_{rm, rn}, v)$. The action of U_i on $\mathcal{H}(k)$ is described by Proposition 3.7. One can check that it commutes with the above isomorphisms for different v , so we get the isomorphism of R -modules. \square

We illustrate the above theorem with the following example (cf. Example 5.8).

Example 4.19. Let us describe the subspaces of $\mathcal{A}_3^{\text{red}}/\mathcal{I}_1$ with various Alexander gradings. The ideal \mathcal{I}_1 equals:

$$\mathcal{I}_1 = ((z_1 - z_2)(z_2 - z_3), (z_1 - z_2)U_3, (z_1 - z_3)U_2, (z_2 - z_3)U_1, U_1U_2, U_1U_3, U_2U_3) \subset \mathcal{A}_3^{\text{red}}.$$

In the Alexander grading $(0, 0, 0)$ one gets

$$[\mathcal{A}_3^{\text{red}}/\mathcal{I}_1](0, 0, 0) \simeq \mathcal{E}_3^{\text{red}}/((z_1 - z_2)(z_2 - z_3)) = \langle 1, z_1 - z_2, z_2 - z_3 \rangle,$$

in the Alexander grading $(k, 0, 0)$ (for $k > 0$) one gets two relations

$$U_1^k(z_1 - z_2)(z_2 - z_3), U_1^{k-1}(z_2 - z_3) \in \mathcal{I}_1.$$

Since the latter implies the former, we get

$$[\mathcal{A}_3^{\text{red}}/\mathcal{I}_1](k, 0, 0) \simeq \mathcal{E}_3^{\text{red}}/(z_2 - z_3) = \langle 1, z_1 - z_2 \rangle.$$

The map $U_1 : [\mathcal{A}_3^{\text{red}}/\mathcal{I}_1](0, 0, 0) \rightarrow [\mathcal{A}_3^{\text{red}}/\mathcal{I}_1](1, 0, 0)$ is a natural projection

$$\mathcal{E}_3^{\text{red}}/((z_1 - z_2)(z_2 - z_3)) \rightarrow \mathcal{E}_3^{\text{red}}/(z_2 - z_3),$$

while the map $U_1 : [\mathcal{A}_3^{\text{red}}/\mathcal{I}_1](k, 0, 0) \rightarrow [\mathcal{A}_3^{\text{red}}/\mathcal{I}_1](k + 1, 0, 0)$ is an isomorphism for $k > 0$.

The gradings $(0, k, 0)$ and $(0, 0, k)$ can be treated similarly. Furthermore, $U_i U_j \in \mathcal{I}_1$ for $i \neq j$, so all other graded subspaces of $\mathcal{A}_3^{\text{red}}/\mathcal{I}_1$ vanish.

Since the multiplication by U_i preserves the ideal \mathcal{I}_β , we get the following useful result.

Corollary 4.20. *If $\max(v) = \max(v - e_i)$, then the map*

$$U_i : \mathrm{HFL}^-(K_{rm, rn}, v) \rightarrow \mathrm{HFL}^-(K_{rm, rn}, v - e_i)$$

is surjective.

Lemma 4.21. *Suppose that $\max(v) = k$ and $\max(v - e_i) = k - 1$, and the homology group $\mathrm{HFL}^-(K_{rm, rn}, v)$ does not vanish. Then $\beta(k) = r - 1, \beta(k - 1) \geq r - 2$ and the map*

$$U_i : \mathrm{HFL}^-(K_{rm, rn}, v) \rightarrow \mathrm{HFL}^-(K_{rm, rn}, v - e_i)$$

is surjective.

Proof. Since $\max(v) = k$ and $\max(v - e_i) = k - 1$, the multiplicity of k in v equals 1, so by Theorem 5 $\beta(k) \geq r - 1$, hence $\beta(k) = r - 1$. Therefore $\mathrm{HFL}^-(K_{rm, rn}, v) \simeq \mathcal{E}_r^{\mathrm{red}}$, so U_i is surjective. Indeed, by Theorem 5 $\mathrm{HFL}^-(K_{rm, rn}, v - e_i)$ is naturally isomorphic to a quotient of $\mathcal{E}_r^{\mathrm{red}}$, and by Proposition 3.7 U_i coincides with a natural quotient map. Finally, by (4.4) $\mathrm{HFK}^-(K_{m, n}, k - c + l(r - 1)) \simeq \mathbb{F}$, and by Lemma 4.6 $\mathrm{HFK}^-(K_{m, n}, k - 1 - c + l(r - 2)) \simeq \mathbb{F}$, so $\beta(k - 1) \geq r - 2$. \square

Proof of Theorem 6. Let us prove that the homology classes with diagonal Alexander gradings generate HFL^- over R . Indeed, given $v = (v_1 \leq \dots \leq v_r)$ with $\mathrm{HFL}^-(K_{rm, rn}, v) \neq 0$, by Theorems 5 and 4.18 one can check that $\mathrm{HFL}^-(K_{rm, rn}, v_r, \dots, v_r) \neq 0$ and by Corollary 4.20 the map

$$U_1^{v_r - v_1} \dots U_{r-1}^{v_r - v_{r-1}} : \mathrm{HFL}^-(K_{rm, rn}, v_r, \dots, v_r) \rightarrow \mathrm{HFL}^-(K_{rm, rn}, v)$$

is surjective.

Let us describe the R -modules generated by the diagonal classes in degree (k, \dots, k) . If $\beta(k) = -1$ then $\mathrm{HFL}^-(K_{rm, rn}, k, \dots, k) = 0$. If $0 \leq \beta(k) \leq r - 2$ then by Lemma 4.21 the submodule $R \cdot \mathrm{HFL}^-(K_{rm, rn}, k, \dots, k)$ does not contain any classes with maximal Alexander degree less than k , so by Theorem 4.18

$$R \cdot \mathrm{HFL}^-(K_{rm, rn}, k, \dots, k) \simeq \mathcal{A}_r^{\mathrm{red}} / \mathcal{I}_{\beta(k)} =: M_{\beta(k)}$$

Suppose that $\beta(k) = r - 1$, and consider minimal a and maximal b such that $a \leq k \leq b$ and $\beta(i) = r - 1$ for $i \in [a, b]$. If there is no minimal a , we set $a = -\infty$. By Lemma 4.21, $\beta(a - 1) = r - 2$ and all the maps

$$\begin{aligned} \mathrm{HFL}^-(K_{rm, rn}, b, \dots, b) &\xrightarrow{U_1 \dots U_r} \mathrm{HFL}^-(K_{rm, rn}, b - 1, \dots, b - 1) \rightarrow \dots \\ &\dots \rightarrow \mathrm{HFL}^-(K_{rm, rn}, a, \dots, a) \xrightarrow{U_1 \dots U_r} \mathrm{HFL}^-(K_{rm, rn}, a - 1, \dots, a - 1) \end{aligned}$$

are surjective. Therefore

$$R \cdot \mathrm{HFL}^-(K_{rm, rn}, b, \dots, b) \simeq \mathcal{A}_r^{\mathrm{red}} / (U_1 \dots U_r)^{b-a} \mathcal{I}_{r-2} =: M_{r-1, b-a+1}$$

is supported in all Alexander degrees with maximal coordinates in $[a, b]$ and in Alexander degrees with maximal coordinate $(a - 1)$ which appears with multiplicity at least 2.

Finally, we get the following decomposition of HFL^- as an R -module:

$$\mathrm{HFL}^-(K_{rm, rn}) = \bigoplus_{\substack{k: 0 \leq \beta(k) < r-1 \\ \beta(k+1) < r-1}} M_{\beta(k)} \oplus \bigoplus_{\substack{a, b: \beta(a-1) = r-2 \\ \beta(b+1) < r-1 \\ \beta([a, b]) = r-1}} M_{r-1, b-a+1} \oplus M_{r-1, \infty}.$$

\square

Note that for $r = 1$ we get $M_{0, l} \simeq \mathbb{F}[U_1] / (U_1^l)$ and $M_{0, +\infty} \simeq \mathbb{F}[U]$.

4.4. Spectral sequence for $\widehat{\text{HFL}}$.

Theorem 4.22. *If $\beta(k) + \beta(k+1) \leq r-2$ then the spectral sequence for $\widehat{\text{HFL}}(K_{rm, rn}, k, \dots, k)$ degenerates at the \widehat{E}_2 page and*

$$\widehat{\text{HFL}}(K_{rm, rn}, k, \dots, k) \simeq \bigoplus_{i=0}^{\beta(k)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)-i} \oplus \bigoplus_{i=0}^{\beta(k+1)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)+2-r+i}.$$

Proof. By Proposition 3.8, for a given v there is a spectral sequence with \widehat{E}_1 page

$$\widehat{E}_1 = \bigoplus_{B \subset \{1, \dots, r\}} \text{HFL}^-(L, v + e_B)$$

and converging to $\widehat{E}_\infty = \widehat{\text{HFL}}(L, v)$. If $v = (k, \dots, k)$ then (for $B \neq \emptyset$) the maximal coordinate of $v + e_B$ equals $k+1$ and appears with multiplicity $\lambda = |B|$. Therefore, by Theorem 5 $\text{HFL}^-(L, v + e_B)$ does not vanish if and only if either $B = \emptyset$ or $|B| \geq r - \beta(k+1)$, and it is given by Theorem 5. By (1.1) we have $\mathbf{h}(k+1) = \mathbf{h}(k) - \beta(k+1) - 1$.

The spectral sequence is bigraded by the homological (Maslov) grading at each vertex of the cube and the “cube grading” $|B|$. The differential $\widehat{\partial}_1$ acts along the edges of the cube, and decreases the Maslov grading by 2 and the cube grading by 1.

One can check using Theorem 4.18 that its homology \widehat{E}_2 does not vanish in cube degrees 0 and $r - \beta(k+1)$, so one can write $\widehat{E}_2 = \widehat{E}_2^0 \oplus \widehat{E}_2^{r-\beta(k+1)}$, and

$$\widehat{E}_2^0 \simeq \bigoplus_{i=0}^{\beta(k)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)-i}, \quad \widehat{E}_2^{r-\beta(k+1)} \simeq \bigoplus_{i=0}^{\beta(k+1)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k+1)-3\beta(k+1)+i}.$$

By (1.1) we have $\mathbf{h}(k+1) = \mathbf{h}(k) - \beta(k+1) - 1$, so $-2\mathbf{h}(k+1) - 3\beta(k+1) + i = -2\mathbf{h}(k) + 2 - \beta(k+1) + i$.

A higher differential $\widehat{\partial}_s$ decreases the cube grading by s and decreases the Maslov grading by $s+1$. Therefore the only nontrivial higher differential is $\widehat{\partial}_{r-\beta(k+1)}$ which vanishes by degree reasons too. Indeed, the maximal Maslov grading in $\widehat{E}_2^{r-\beta(k+1)}$ equals $-2\mathbf{h}(k) + 2$ while the minimal Maslov grading in \widehat{E}_2^0 equals $-2\mathbf{h}(k) - \beta(k)$, so the differential can decrease the Maslov grading at most by $\beta(k) + 2$. On the other hand, $\widehat{\partial}_{r-\beta(k+1)}$ drops it by $r - \beta(k+1) + 1$, and for $\beta(k) + \beta(k+1) < r - 1$ one has $r - \beta(k+1) + 1 > \beta(k) + 2$. Therefore $\widehat{\partial}_{r-\beta(k+1)} = 0$ and the spectral sequence vanishes at the \widehat{E}_2 page. \square

We illustrate the proof of Theorem 4.22 by Examples 5.4 and 5.5

Lemma 4.23. *The following identity holds:*

$$\beta(1-k) + \beta(k) = r - 2.$$

Proof. By (1.1) and Lemma 4.5 we have

$$\beta(k) = h(k-1, \dots, k-1) - h(k, \dots, k) - 1, \quad \beta(1-k) = h(-k, \dots, -k) - h(1-k, \dots, 1-k) - 1.$$

By Lemma 4.4 we have

$$h(-k, \dots, -k) = h(k, \dots, k) + kr, \quad h(1-k, \dots, 1-k) = h(k-1, \dots, k-1) + r(k-1).$$

These two identities imply the desired statement. \square

Theorem 4.24. *If $\beta(k) + \beta(k+1) \geq r-2$ then:*

$$\widehat{\text{HFL}}(K_{rm, rn}, k, \dots, k) \simeq \bigoplus_{i=0}^{r-2-\beta(k+1)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)-i} \oplus \bigoplus_{i=0}^{r-2-\beta(k)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(k)+2-r+i}$$

Proof. By Lemma 4.23 we get $\beta(-k) = r-2-\beta(k+1)$ and $\beta(1-k) = r-2-\beta(k)$, so

$$\beta(k) + \beta(k+1) + \beta(-k) + \beta(1-k) = 2(r-2),$$

so $\beta(-k) + \beta(1-k) \leq r-2$. By Theorem 4.22 the spectral sequence degenerates for $\widehat{\text{HFL}}(-k, \dots, -k)$ and

$$\widehat{\text{HFL}}(K_{rm, rn}, -k, \dots, -k) \simeq \bigoplus_{i=0}^{r-2-\beta(k+1)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(-k)-i} \oplus \bigoplus_{i=0}^{r-2-\beta(k)} \binom{r-1}{i} \mathbb{F}_{-2\mathbf{h}(-k)+2-r+i}$$

Finally, by [OS08, Proposition 8.2] we have

$$\widehat{\text{HFL}}_{\bullet}(K_{rm, rn}, k, \dots, k) = \widehat{\text{HFL}}_{\bullet-2kr}(K_{rm, rn}, -k, \dots, -k)$$

and by Lemma 4.4 $\mathbf{h}(k) = \mathbf{h}(-k) - kr$. □

Theorem 4.25. *Off-diagonal homology groups are supported on the union of the unit cubes along the diagonal. In such a cube with corners (k, \dots, k) and $(k+1, \dots, k+1)$ one has*

$$\widehat{\text{HFL}}(K_{rm, rn}, (k-1)^j, k^{r-j}) \simeq \binom{r-2}{\beta(k)} \mathbb{F}_{-2\mathbf{h}(k)-\beta(k)-j}.$$

Proof. We use the spectral sequence from HFL^- to $\widehat{\text{HFL}}$. By Theorem 4.18, all the \widehat{E}_2 homology outside the union of these cubes vanish (since some U_i would provide an isomorphism between $\text{HFL}^-(K_{rm, rn}, v)$ and $\text{HFL}^-(K_{rm, rn}, v - e_i)$). Furthermore, if $\beta(k) = r-1$ then the homology in the cube vanish too, so we can focus on the case $\beta(k) \leq r-2$.

One can check that \widehat{E}_2 does not vanish in cube degrees $j - \beta(k), \dots, j$ and

$$\widehat{E}_2^{j-c} \simeq \binom{j-1}{c} \binom{r-1-j}{\beta(k)-c} \mathbb{F}_{-2\mathbf{h}(k)-\beta(k)-c}.$$

Note that the *total* homological degree on \widehat{E}_2^{j-c} equals $-2\mathbf{h}(k) - \beta(k) - j$ and does not depend on c . Therefore all higher differentials in the spectral sequence must vanish and the rank of $\widehat{\text{HFL}}$ equals:

$$\sum_{c=0}^{\beta} \binom{j-1}{c} \binom{r-1-j}{\beta(k)-c} = \binom{r-2}{\beta(k)}.$$

□

We illustrate this proof by Example 5.6.

4.5. Special case: $m = 1, n = 2g(K) - 1$. The case $m = 1, n = 2g(K) - 1$ is special since Lemma 4.6 is not always true. Indeed, $K_{m, n} = K$ and $l = n = 2g(K) - 1$, but for $v = g(K) - l = 1 - g(K)$ we have $\text{HFL}^-(K, v) = 0$. However, it is clear that in all other cases Lemma 4.6 is true, so for generic v Lemmas 4.8 and 4.10 hold true. This allows one to prove an analogue of Theorem 5.

Theorem 4.26. *Assume that $m = 1, n = 2g(K) - 1$ (so $l = 2g(K) - 1$) and suppose that $v = (u_1^{\lambda_1}, u_2^{\lambda_2}, \dots, u_s^{\lambda_s})$ where $u_1 < \dots < u_s$. Then the Heegaard-Floer homology group $\text{HFL}^-(K_{rm, rn}, v)$ can be described as following:*

(a) Assume that $u_s - c + l(r - \lambda_s) = g(K) - \nu l$ with $1 \leq \nu \leq \lambda_s$. Then

$$\mathrm{HFL}^-(K_{rm, rn}, v) \simeq (\mathbb{F}_{(0)} \oplus \mathbb{F}_{(-1)})^{r-\lambda_s} \otimes \left[\bigoplus_{j=0}^{\nu-2} \binom{\lambda_s-1}{j} \mathbb{F}_{(-2h(v)-j)} \oplus \binom{\lambda_s-1}{\nu} \mathbb{F}_{(-2h(v)+2-\nu)} \right]$$

(b) In all other cases, the homology is given by Theorem 5.

Proof. One can check that the proof of Lemma 4.8 fails if $u_s - c + l(r - \lambda_s) = g(K) - l$, and remains true in all other cases. Similarly, the proof of Lemma 4.10 fails only if $u_s - c + l(r - \lambda_s) + lj = g(K) - l$ for $1 \leq j \leq \lambda_s - 1$, which is equivalent to $u_s - c + l(r - \lambda_s) = g(K) - (j + 1)l$. This proves (b).

Let us consider the special case (a). Note that

$$h_{m,n}(u_s - c + l(r - \lambda_s) + lj - 1) - h_{m,n}(u_s - c + l(r - \lambda_s) + lj) = \begin{cases} 1, & \text{if } j < \nu - 1 \\ 0, & \text{if } j = \nu - 1 \\ 1, & \text{if } j = \nu \\ 0, & \text{if } j > \nu. \end{cases}$$

Given a pair of subsets $B' \subset \{1, \dots, r - \lambda_s\}$ and $B'' \subset \{r - \lambda_s + 1, \dots, r\}$, one can write, analogously to Lemma 4.10:

$$h_{rm, rn}(v - e_{B'} - e_{B''}) = h_{rm, rn}(v) + |B'| + w(B''),$$

where

$$w(B'') = \begin{cases} |B''|, & \text{if } |B''| \leq \nu - 1 \\ \nu - 1, & \text{if } |B''| = \nu \\ \nu, & \text{if } |B''| > \nu. \end{cases}$$

By the Künneth formula, the E_2 page of the spectral sequence is determined by the “deformed cube homology” with the weight function $w(B'')$, as in (4.5). If ∂ , as above, denotes the standard cube differential, then, similarly to Lemma 4.14, the homology of ∂_U^w is isomorphic to the kernel of ∂ in cube degrees $0, \dots, \nu - 2$ and ν .

Finally, we need to prove that all higher differentials vanish. For a homology generator α on the E_2 page of cube degree x , its bidegree is equal either to $(x, -2h(v) - 2x)$ or to $(x, -2h(v) - 2x + 2)$. The differential ∂_k has bidegree $(-k, k - 1)$ (see Remark 3.6), so the bidegree of $\partial_k(\alpha)$ is equal either to $(x - k, -2h(v) - 2x + k - 1)$ or to $(x - k, -2h(v) - 2x + k + 1)$. Since $-2x + k + 1 < -2(x - k)$ for $k > 1$, we have $\partial_k(\alpha) = 0$. \square

The action of U_i in this special case can be described similarly to Theorem 4.18. However, it is not true that U_i is surjective whenever it does not obviously vanish. In particular, the following example shows that HFL^- may be not generated by diagonal classes, so Theorem 6 does not hold. We leave the appropriate adjustment of Theorem 6 as an exercise to a reader.

Example 4.27. Consider $T_{2,2}$, the $(2, 2)$ cable of the trefoil. We have $g(K) = l = 1$ and $c = 1/2$, so by Theorem 4.26

$$\mathrm{HFL}^-(T_{2,2}, 1/2, 1/2) \simeq \mathbb{F}_{(-1)}, \quad \mathrm{HFL}^-(T_{2,2}, -1/2, 1/2) \simeq \mathbb{F}_{(-2)} \oplus \mathbb{F}_{(-3)}.$$

Therefore U_1 is not surjective. Furthermore, the class in $\mathrm{HFL}^-(T_{2,2}, -1/2, 1/2)$ of homological degree (-2) is not in the image of any diagonal class under the R -action.

5. EXAMPLES

5.1. (n, n) torus links. The symmetrized multi-variable Alexander polynomial of the (n, n) torus link equals (for $n > 1$):

$$\Delta_{T_{n,n}}(t_1, \dots, t_n) = ((t_1 \cdots t_n)^{1/2} - (t_1 \cdots t_n)^{-1/2})^{n-2}.$$

Each pair of components has linking number 1, so $c = (n-1)/2$. The homology groups $\mathrm{HFL}^-(T(n, n), v)$ are described by the following theorem, which is a special case of Theorem 5.

Theorem 5.1. *Consider the (n, n) torus link, and an Alexander grading $v = (v_1, \dots, v_n)$. Suppose that among the coordinates v_i exactly λ are equal to k and all other coordinates are less than k . Let $|v| = v_1 + \dots + v_n$. Then*

$$\mathrm{HFL}^-(T(n, n), v) = \begin{cases} 0 & \text{if } k > \lambda - \frac{n+1}{2}, \\ (\mathbb{F}_{(0)} \oplus \mathbb{F}_{(-1)})^{n-1} \otimes \mathbb{F}_{2|v|} & \text{if } k < -\frac{n-1}{2}, \\ (\mathbb{F}_{(0)} \oplus \mathbb{F}_{(-1)})^{n-\lambda} \otimes \bigoplus_{i=0}^{\lambda - \frac{n+1}{2} - k} \binom{\lambda-1}{i} \mathbb{F}_{(-2h(v)-i)} & \text{if } -\frac{n-1}{2} \leq k \leq \lambda - \frac{n+1}{2}, \end{cases}$$

where $h(v) = \frac{1}{2}(\frac{n-1}{2} - k)(\frac{n-1}{2} - k + 1) + kn - |v|$ in the last case.

Proof. Indeed, $\beta(k) = \frac{n-1}{2} - k$ for $k > -\frac{n-1}{2}$ and $\beta(k) = n-1$ for $k \leq -\frac{n-1}{2}$. By Theorem 5, the homology group $\mathrm{HFL}^-(T(n, n), v)$ does not vanish if and only if

$$(5.1) \quad k \leq \lambda - \frac{n+1}{2}.$$

If $k \geq -\frac{n-1}{2}$, equation (4.3) implies:

$$h_{n,n}(v) = \frac{1}{2} \left(\frac{n-1}{2} - k \right) \left(\frac{n-1}{2} - k + 1 \right) + kn - |v|.$$

If $k \leq -\frac{n-1}{2}$, equation (4.3) implies $h_{n,n}(v) = -|v|$. Furthermore, for all v satisfying (5.1) one has

$$\mathrm{HFL}^-(T(n, n), v) = (\mathbb{F}_{(0)} \oplus \mathbb{F}_{(-1)})^{n-\lambda} \otimes \bigoplus_{j=0}^{\lambda - \frac{n+1}{2} - k} \binom{\lambda-1}{j} \mathbb{F}_{(-2h_{n,n}(v)-j)}.$$

Finally, if $k = -\frac{n-1}{2}$, then (5.1) holds for all λ and $\lambda - \frac{n+1}{2} - k > \lambda - 1$, hence

$$\mathrm{HFL}^-(T(n, n), v) = (\mathbb{F}_{(0)} \oplus \mathbb{F}_{(-1)})^{n-\lambda} \otimes \bigoplus_{j=0}^{\lambda-1} \binom{\lambda-1}{j} \mathbb{F}_{(-2h_{n,n}(v)-j)} = (\mathbb{F}_{(0)} \oplus \mathbb{F}_{(-1)})^{n-1} \otimes \mathbb{F}_{(-2h_{n,n}(v))}.$$

□

Remark 5.2. One can check that, in agreement with [GN15], the condition (5.1) defines the multi-dimensional semigroup of the plane curve singularity $x^n = y^n$.

Corollary 5.3. *We have the following decomposition of HFL^- as an R -module:*

$$\mathrm{HFL}^-(T(n, n)) = M_0 \oplus M_1 \oplus M_2 \oplus \dots \oplus M_{n-2} \oplus M_{n-1, +\infty}.$$

To prove Theorem 4, we use Theorem 3.

Proof of Theorem 4. We have $\beta(\frac{n-1}{2} - s) = s$ for $s < n-1$, and

$$\beta\left(\frac{n-1}{2} - s\right) + \beta\left(\frac{n-1}{2} - s + 1\right) = 2s - 1 \leq n - 2 \leq s \leq \frac{n-1}{2}.$$

Therefore for $s \leq \frac{n-1}{2}$ Theorem 4.22 implies the degeneration of the spectral sequence from HFL^- to $\widehat{\text{HFL}}$, and

$$\widehat{\text{HFL}} \left(T(n, n), \frac{n-1}{2} - s, \dots, \frac{n-1}{2} - s \right) = \bigoplus_{i=0}^s \binom{n-1}{i} \mathbb{F}_{(-s^2-s-i)} \oplus \bigoplus_{i=0}^{s-1} \binom{n-1}{i} \mathbb{F}_{(-s^2-s-n+2+i)}.$$

□

Let us illustrate the degeneration of the spectral sequence from HFL^- to $\widehat{\text{HFL}}$ in some examples.

Example 5.4. For $s = 0$ we have $\widehat{E}_1 = \widehat{E}_2 = \mathbb{F}_{(0)}$. For $s = 1$ the \widehat{E}_1 page has nonzero entries in cube degree 0 where one gets

$$\text{HFL}^- \left(T(n, n), \frac{n-1}{2} - 1, \dots, \frac{n-1}{2} - 1 \right) \simeq \mathbb{F}_{(-2)} \oplus (n-1)\mathbb{F}_{(-3)},$$

and in cube degree n where one gets $\mathbb{F}_{(0)}$. Indeed, the differential $\widehat{\partial}_1$ vanishes, so for $n > 2$

$$\widehat{\text{HFL}} \left(T(n, n), \frac{n-1}{2} - 1, \dots, \frac{n-1}{2} - 1 \right) \simeq \mathbb{F}_{(-2)} \oplus (n-1)\mathbb{F}_{(-3)} \oplus \mathbb{F}_{(-n)}.$$

Note that for $n = 2$ the differential $\widehat{\partial}_2$ does not vanish, so the bound $s \leq \frac{n-1}{2}$ is indeed necessary for the spectral sequence to collapse at \widehat{E}_2 page.

Example 5.5. The case $s = 2$ is more interesting. The \widehat{E}_1 page has nonzero entries in cube degree 0, $n-1$ (where we have n vertices) and n , where one has

$$\widehat{E}_1^0 = \mathbb{F}_{(-6)} \oplus (n-1)\mathbb{F}_{(-7)} \oplus \binom{n-1}{2} \mathbb{F}_{(-8)}, \quad \widehat{E}_1^{n-1} = n(\mathbb{F}_{(-4)} \oplus \mathbb{F}_{(-5)}), \quad \widehat{E}_1^n = \mathbb{F}_{(-2)} \oplus (n-1)\mathbb{F}_{(-3)}.$$

The differential $\widehat{\partial}_1$ cancels some summands in \widehat{E}_1^{n-1} and \widehat{E}_1^n ;

$$\widehat{E}_2^0 = \mathbb{F}_{(-6)} \oplus (n-1)\mathbb{F}_{(-7)} \oplus \binom{n-1}{2} \mathbb{F}_{(-8)}, \quad \widehat{E}_2^{n-1} = (n-1)\mathbb{F}_{(-4)} + \mathbb{F}_{(-5)}.$$

For $n > 4$ all higher differentials vanish and

$$(5.2) \quad \widehat{\text{HFL}} \left(T(n, n), \frac{n-1}{2} - 2, \dots, \frac{n-1}{2} - 2 \right) \simeq \mathbb{F}_{(-6)} \oplus (n-1)\mathbb{F}_{(-7)} \oplus \binom{n-1}{2} \mathbb{F}_{(-8)} \oplus (n-1)\mathbb{F}_{(-3-n)} + \mathbb{F}_{(-4-n)}.$$

The following example illustrates the computation of $\widehat{\text{HFL}}$ for the off-diagonal Alexander gradings.

Example 5.6. Let us compute the homology $\widehat{\text{HFL}}(T(n, n), v)$ for $v = (\frac{n-1}{2} - 2)^j (\frac{n-1}{2} - 1)^{n-j}$ ($1 \leq j \leq n-1$) using the spectral sequence from HFL^- . In the n dimensional cube $(v + e_B)$ almost all all vertices have vanishing HFL^- , except for the vertex $(\frac{n-1}{2} - 1, \dots, \frac{n-1}{2} - 1)$

$$\text{HFL}^- \left(\frac{n-1}{2} - 1, \dots, \frac{n-1}{2} - 1 \right) = \mathbb{F}_{(-2)} \oplus (n-1)\mathbb{F}_{(-3)}$$

and j of its neighbors with homology $\mathbb{F}_{(-4)} \oplus \mathbb{F}_{(-5)}$. Clearly, \widehat{E}_2 is concentrated in degrees j (with homology $(n-1-j)\mathbb{F}_{(-3)}$) and $(j-1)$ (with homology $(j-1)\mathbb{F}_{(-4)}$). Note that both parts contribute to the total degree $(-3-j)$, so

$$\widehat{\text{HFL}}(T(n, n), v) = (n-1-j)\mathbb{F}_{(-3-j)} \oplus (j-1)\mathbb{F}_{(-3-j)} = (n-2)\mathbb{F}_{(-3-j)}.$$

Finally, we draw all the homology groups HFL^- for $(2, 2)$ and $(3, 3)$ torus links.

Example 5.7. For the Hopf link, one has two cases. If $v_1 < v_2$, then the condition (5.1) implies $v_2 \leq -1/2$. If $v_1 = v_2$, then (5.1) implies $v_2 \geq 1/2$.

The nonzero homology of the Hopf link is shown in Figure 3 and Table 1

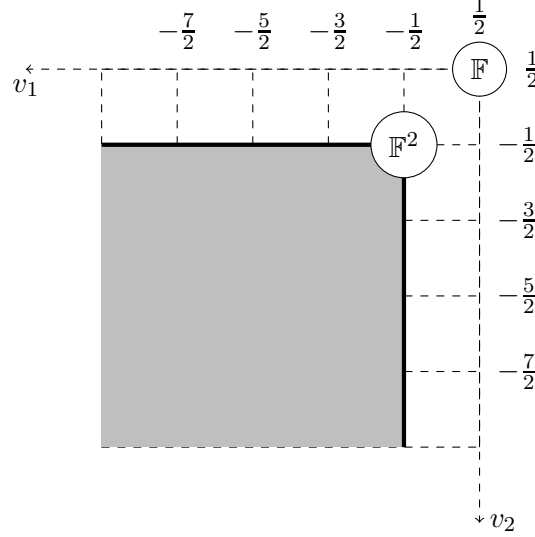


FIGURE 3. HFL^- for the $(2,2)$ torus link: \mathbb{F}^2 on thick lines and in the grey region

Alexander grading	Homology
$(1/2, 1/2)$	$\mathbb{F}_{(0)}$
$(a, b), a, b \leq -1/2$	$\mathbb{F}_{(2a+2b)} \oplus \mathbb{F}_{(2a+2b-1)}$

TABLE 1. Maslov gradings for the $(2, 2)$ torus link

Example 5.8. For the $(3, 3)$ torus link, one has two cases. If $v_1 \leq v_2 < v_3$, then the condition (5.1) implies $v_3 \leq 1$. If $v_1 < v_2 = v_3$, then (5.1) implies $v_3 \leq 0$. Finally, if $v_1 = v_2 = v_3$, then (5.1) implies $v_3 \leq 1$. In other words, nonzero homology appears at the point $(1, 1, 1)$, at three lines $(0, 0, k), (0, k, 0), (k, 0, 0)$ ($k \leq 0$) and at the octant $\max(v_1, v_2, v_3) \leq -1$.

This homology is shown in Figure 4 and Table 2.

Alexander grading	Homology
$(1, 1, 1)$	$\mathbb{F}_{(0)}$
$(0, 0, 0)$	$\mathbb{F}_{(-2)} \oplus 2\mathbb{F}_{(-3)}$
$(0, 0, k), (0, k, 0)$ and $(k, 0, 0)$ ($k < 0$)	$\mathbb{F}_{(2k-2)} \oplus \mathbb{F}_{(2k-3)}$
$(a, b, c), a, b, c \leq -1$	$\mathbb{F}_{(2a+2b+2c)} \oplus 2\mathbb{F}_{(2a+2b+2c-1)} \oplus \mathbb{F}_{(2a+2b+2c-2)}$

TABLE 2. Maslov gradings for the $(3, 3)$ torus link

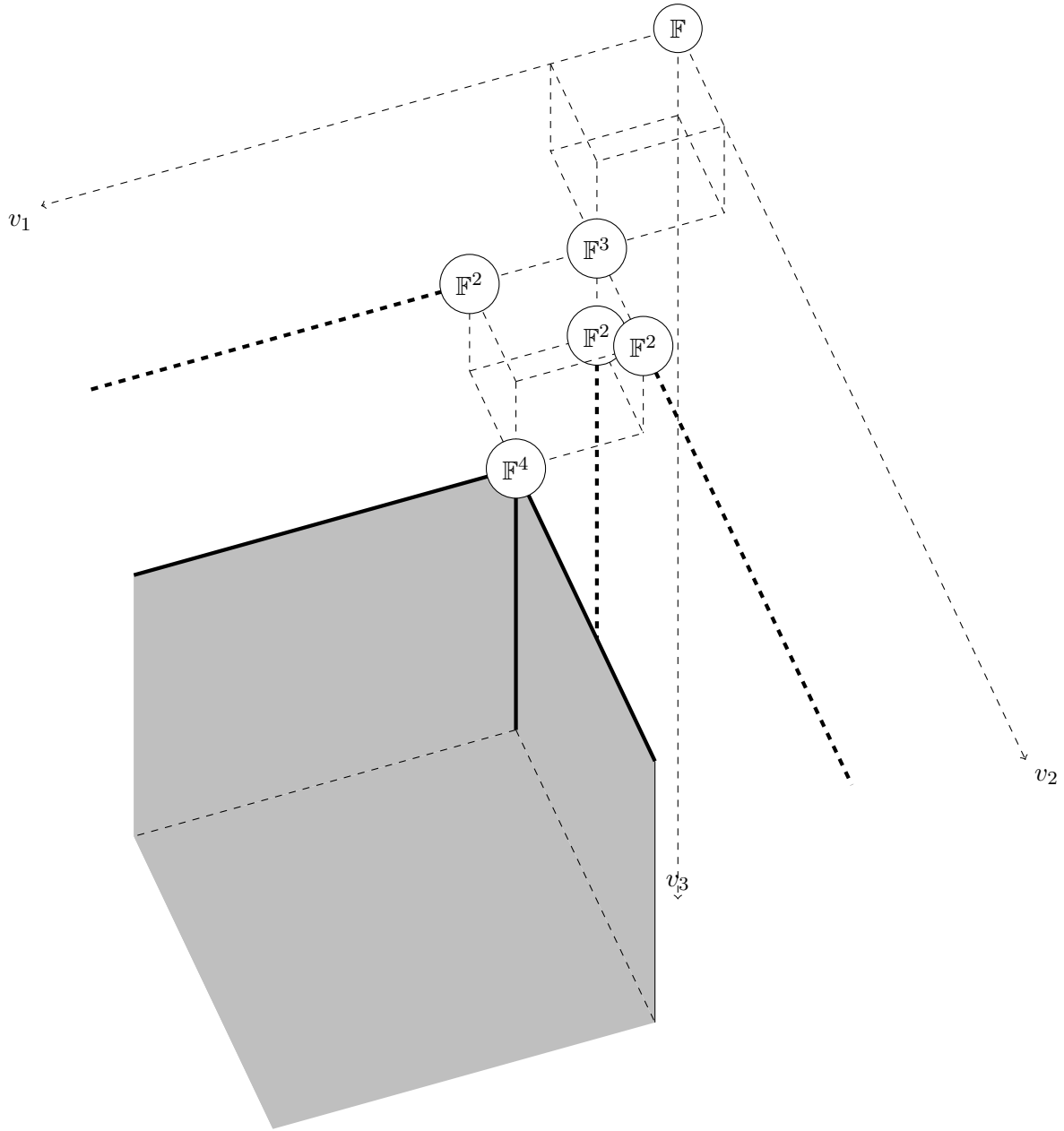
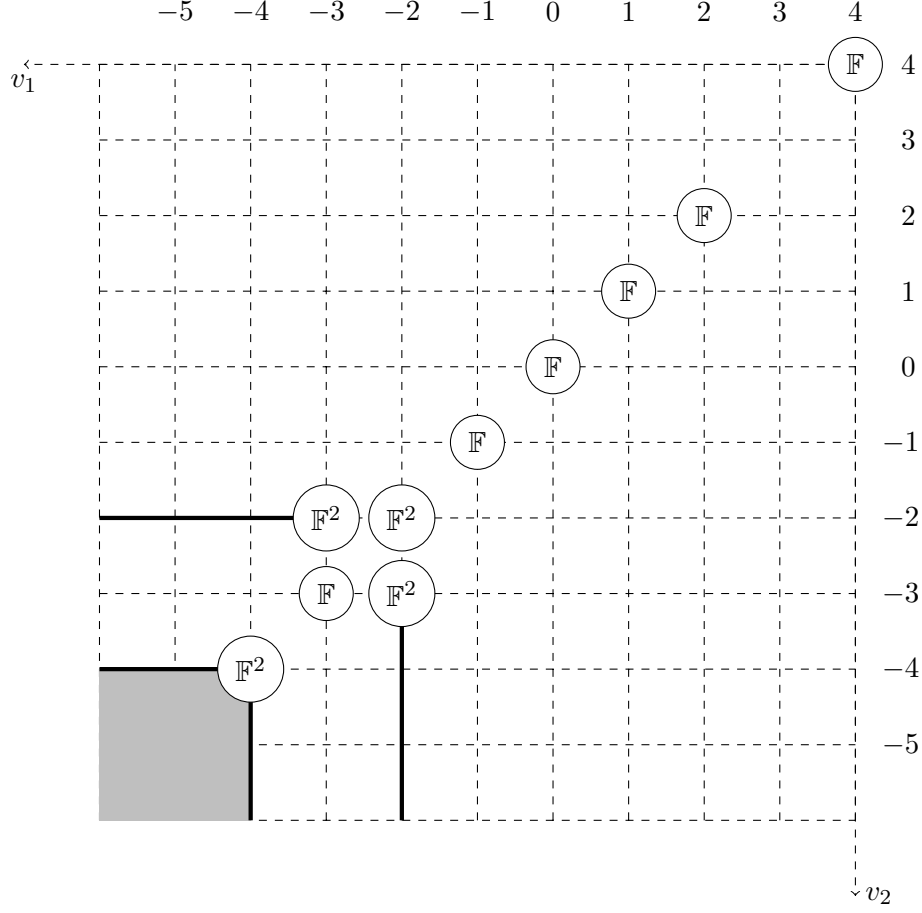


FIGURE 4. HFL^- for the $(3,3)$ torus link: \mathbb{F}^2 on dashed thick lines; \mathbb{F}^4 on solid thick lines and in the shaded region. Top Alexander grading is $(1, 1, 1)$.

5.2. More general torus links. The HFL^- homology of the $(4, 6)$ torus link is shown in Figure 5 and Table 3. Note that as an $\mathbb{F}[U_1, U_2]$ module it can be decomposed into 5 copies of $M_0 \simeq \mathbb{F}$, a copy of $M_{1,1}$ and a copy of $M_{1,+\infty}$. In particular, the map $U_1 U_2 : \text{HFL}^-(-2, -2) \rightarrow \text{HFL}^-(-3, -3)$ is surjective with one-dimensional kernel.

5.3. Non-algebraic example. In this subsection we compute the Heegaard-Floer homology for the $(4, 6)$ -cable of the trefoil. Its components are $(2, 3)$ -cables of the trefoil, which are known to be

FIGURE 5. HFL^- for the $(4,6)$ torus link: \mathbb{F}^2 on thick lines and in the grey region

Alexander grading	Homology
$(4, 4)$	$\mathbb{F}_{(0)}$
$(2, 2)$	$\mathbb{F}_{(-2)}$
$(1, 1)$	$\mathbb{F}_{(-4)}$
$(0, 0)$	$\mathbb{F}_{(-6)}$
$(-1, -1)$	$\mathbb{F}_{(-8)}$
$(-2, k)$ and $(k, -2)$, $k \leq -2$	$\mathbb{F}_{(2k-6)} \oplus \mathbb{F}_{(2k-7)}$
$(-3, -3)$	$\mathbb{F}_{(-12)}$
(a, b) , $a, b \leq -4$	$\mathbb{F}_{(2a+2b)} \oplus \mathbb{F}_{(2a+2b-1)}$

TABLE 3. Maslov gradings for the $(4, 6)$ torus link

L-space knots (cf. [Hed09]), but not algebraic knots. By Theorem 2, the $(4,6)$ -cable of the trefoil is an L-space link, but its homology is not covered by [GN15].

The Alexander polynomial of the $(2, 3)$ -cable of the trefoil equals:

$$\Delta_{T_{2,3}}(t) = \frac{(t^6 - t^{-6})(t^{1/2} - t^{-1/2})}{(t^{3/2} - t^{-3/2})(t^2 - t^{-2})},$$

hence the Euler characteristic of its Heegaard-Floer homology equals

$$\chi_{2,3}(t) = \frac{\Delta_{T_{2,3}}(t)}{1 - t^{-1}} = t^3 + 1 + t^{-1} + t^{-3} + t^{-4} + \dots$$

By (4.1), the bivariate Alexander polynomial of the $(4, 6)$ -cable equals:

$$\begin{aligned} \chi_{4,6}(t_1, t_2) &= \chi_{2,3}(t_1 \cdot t_2)((t_1 t_2)^3 - (t_1 t_2)^{-3}) \\ &= (t_1 t_2)^6 + (t_1 t_2)^3 + (t_1 t_2)^2 + (t_1 t_2)^{-1} + (t_1 t_2)^{-2} + (t_1 t_2)^{-5}. \end{aligned}$$

The nonzero Heegaard-Floer homology are shown in Figure 6 and the corresponding Maslov gradings are given in Table 4. Note that as $\mathbb{F}[U_1, U_2]$ module it can be decomposed in the following way:

$$\text{HFL}^- \simeq 4M_0 \oplus M_{1,1} \oplus M_{1,2} \oplus M_{1,+\infty}.$$

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Alexander grading	Homology
$(6, 6)$	$\mathbb{F}_{(0)}$
$(3, 3)$	$\mathbb{F}_{(-2)}$
$(2, 2)$	$\mathbb{F}_{(-4)}$
$(0, k)$ and $(k, 0)$, $k \geq 0$	$\mathbb{F}_{(2k-6)} \oplus \mathbb{F}_{(2k-7)}$
$(-1, -1)$	$\mathbb{F}_{(-10)}$
$(-2, -2)$	$\mathbb{F}_{(-12)}$
$(-3, k)$ and $(k, -3)$, $k \geq -3$	$\mathbb{F}_{(2k-8)} \oplus \mathbb{F}_{(2k-9)}$
$(-4, k)$ and $(k, -4)$, $k \geq 10$	$\mathbb{F}_{(2k-10)} \oplus \mathbb{F}_{(2k-11)}$
$(-5, -5)$	$\mathbb{F}_{(-22)}$
(a, b) , $a, b \leq -6$	$\mathbb{F}_{(2a+2b)} \oplus \mathbb{F}_{(2a+2b-1)}$

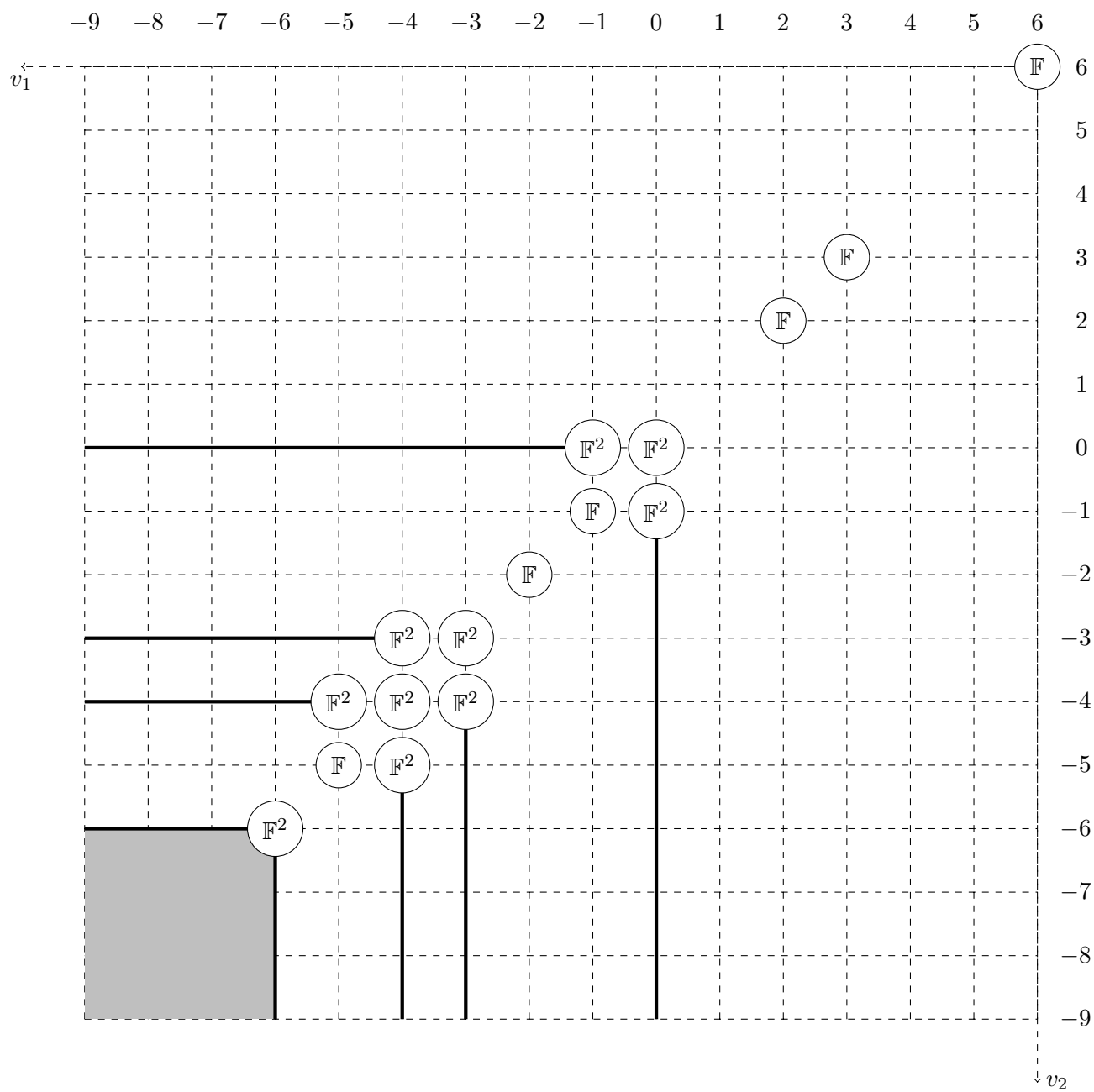
TABLE 4. Maslov gradings for the $(4,6)$ cable of the trefoil

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FIGURE 6. HFL^- for the $(4,6)$ cable of the trefoil: \mathbb{F}^2 on thick lines and in the grey region